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PROCEEDINGS OF

THE EIGHTEENTH GENERAL MEETING OF THE AMERICAN TOWING TANK CONFERENCE

VOLUME THREE

MANEUVERING SESSION

SYSTEMS AND TECHNIQUES SESSION

23–25 AUGUST 1977

ANNAPOLIS, MARYLAND

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PROCEEDINGS OF

THE ~~EIGHTEENTH~~ (18th) GENERAL MEETING OF THE

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Volume III.

MANEUVERING SESSION

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Annapolis, Maryland

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Bruce Nehrling

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VOLUME III

INTRODUCTION

The Technical Committee on Steering and Maneuvering for the 18th American Towing Tank Conference (ATTC) was established by the Executive Committee following the 17th ATTC.

Committee membership is:

H. Eda (Davidson Laboratory)
P. Leone (Institute De Pesquisas Technologicas)
M. Parsons (University of Michigan)
W. Smith, Chairman (David W. Taylor Naval Ship R&D Center)
W. Webster (University of California)

During the intervening period since the last ATTC there has been a remarkable increase in the number and types of closed loop control systems developed for marine vehicles. Such systems are required for a variety of marine craft; e.g., submarines, surface ships, hydrofoils, and air cushion vehicles. In each of the control systems developed so far, the following problems have limited their effective and efficient design.

(a) The availability of a sufficiently accurate mathematical model of the craft.
(b) The use of an efficient simulation of the craft along with modern control theory in the development of control algorithms.
(c) The use of simulation and operational requirements to develop craft performance criteria.
(d) The use of free running models (FRM) to evaluate the control performance of a particular craft design.

In view of the above, as various control systems are implemented and evaluated, the items listed below are becoming obvious:

(a) The controller design is often deficient which is directly traceable to shortcomings in the mathematical model of the craft and its environment.
(b) Improvements in control system performance are almost completely dependent upon the availability of an improved mathematical model of the craft and environment.

(c) Obtaining a satisfactory model of the craft and its associated hydrodynamic parameters is by far the most difficult aspect of the control system design and, accordingly, are obtained with the least accuracy.

(d) Deficiencies in the craft model and their effect on control system design are greatly magnified as craft speeds increase.

The difficulties encountered with craft modeling are, of course, only a restatement of the basic problems which members of the Tow Tank Community are continually addressing. However, there is a significant increase in importance of control system design due to the greater stringencies imposed by higher speeds and the related increase in importance of unsteady effects at high speeds. Therefore, a description of the marine vehicle modeling process and its implications for the Towing Tank Community was established as the principle theme for this committee's effort.

MARINE VEHICLE MODELING TECHNOLOGY

Mathematical modeling technology of marine vehicles is directed toward the determination of a set of differential equations whose solutions, for varous initial conditions and and control inputs, closely represent the behavior of the vehicle. The complexity of the dynamic and hydrodynamic interactions which characterize non-steady-state vehicle motion requires advanced testing and analysis to develop such equations of motion. The conventional craft of thirty years ago were subject to speed limitations imposed by low output power plants. The resulting low hydrodynamic forces led to comparatively simple dynamic behavior having time constants slow enough to be anticipated by helmsmen. Today's high speed vehicles, on the other hand, can perform complex maneuvers at high speeds. The resulting hydrodynamic forces interact with the vehicle motion in complex fashions which must be well understood if the full capability of today's vehicles is to be realized and if improved marine vehicles are to be designed in the future.

This review first details the two main uses of vehicle dynamic models: simulation and design analysis. Secondly, the review summarizes the three main approaches to the determination of the models: theoretical analysis, tank testing, and free running vehicle (full or reduced scale) maneuvering tests.

THE REQUIREMENT FOR VEHICLE DYNAMIC MODELS

The dynamic model of a marine vehicle is a model which predicts the vehicles complete transient motion time history response to arbitrary control inputs and initial conditions. Such a model is useful because of its motion prediction capability and because it provides insight which may be useful in hull or control system design. For example, many design decisions regarding a submarine hull can be made rationally only with a thorough understanding of the hydrodynamic effects on the submarine's dynamic behavior. Such decisions include:

(1) the placement and size of rudder fins, and other control surfaces, and
(2) the utility of innovative configurations; e.g., multiple rudders, roll stabilization, etc.

Clearly, if the handling characteristics resulting from both conventional and unconventional configurations can be modeled, then the relative advantages and disadvantages of the new design can be isolated and quantified. An accurate model of vehicle handling qualities, for example, is required for the design and evaluation of high performance closed-loop autopilots. Low bandwidth autopilots have slow response times. Their performance is not greatly sensitive to the accuracy of the dynamic behavior of the vessel used in control design. The use of an inaccurate model for the design of a high bandwidth controller, however, may lead to degraded and possibly unstable behavior in the actual implementation.

The relative utility of empirical versus phenomenological hydrodynamic models should also be mentioned. A purely empirical model of the hydrodynamic forces and moments acting on the submarine results from simple curve fitting of experimental data. The curve types themselves (e.g., polynomial, exponential, integral functions of the states, etc.) can be chosen using statistical data analysis techniques. The purely empirical approach, then, makes little use of knowledge of the underlying hydrodynamic processes involved in the submarine motion.

Contrast the empirical model with the purely phenomenological model. The purely phenomenological model is derived entirely from theoretical considerations (e.g., potential flow theory, viscid flow theory, etc.). Phenomenological models are highly complex, and their accuracy is highly dependent on assumptions which are difficult to evaluate from experimental data. Clearly, a model development program requires a compromise between the two extremes. The overall approach which will be taken in this report will use the results of hydrodynamic analysis to provide the comprehensive form of the hydrodynamic model. Statistical data analysis techniques will isolate groups of terms from the complete model which are significant during a specific maneuver. Finally, parameter estimation methods will determine the numerical values of the unknown parameters.

The empirical approach will often lead to a good fit of experimental data; however, the resulting model may not acceptably predict the behavior of the vehicle during maneuvers which differ significantly from those in the experimental data. Also, the empirical model may give little insight into the behavior of radically new, untested, hull configurations. The phenomenological/empirical modeling technique outlined in this report is designed to utilize the advantages and to minimize the disadvantages of both of these models.

DETERMINATION OF MODELS

This section will outline the three basic approaches (mathematical analysis, towing tank tests, and free running vehicle tests) to the determination of vehicle dynamic models and will use the submarine as

an example. The purpose here is to summarize the contributions of each method. The section on free running vehicle tests will pay special attention to the complex data processing algorithms which are required in order to develop a generalized model from the specific measurement time history data which results from such tests.

Theoretical Analysis

For theoretical analysis of vehicle dynamics, the vehicle is modeled as a rigid body moving through a viscous fluid. This analysis can be broken down into several components. Some of these components are well understood; others are not.

The kinematics and dynamics of a rigid body acted upon by arbitrary forces and moments has been well understood since Euler. The problem then is the calcuulation of the forces and moments due to the fluid. The hydrostatic forces are again well understood. The hydrodynamic effects can be split into two classes: (a) those that would be present in an inviscid fluid, and (b) those that are due to the viscosity in the fluid. Inviscid fluid effects may be complex for a body of arbitrary shape, but can be calculated using a modern digital computer of moderate capacity. Added hydrodynamic mass is an important inviscid effect. Methods for calculating added mass effects for bodies of revolution having fin-like appendages have been demonstrated.

Viscous fluid dynamics effects are difficult at present to predict accurately and consistently. For example, several efforts have been directed specifically at submarines. Reference 5 analytically determines the forces and moments on a submarine hull using slender body theory for unseparated flow. Experimental data on the location of the flow separation point for an inclined body is used with the theory to predict forces and moments for angles-of-attack of up to 20 degrees. Comparisons with experimental data for a specific submarine configuration indicates that the theory predicts well the onset and the qualitative nature of nonlinear effects. But quantitative agreement is only fair. Reference 6 extends this work by developing methods for theoretically predicting the forces and moments on the hull and stern control surfaces by the

vortex wake shed from the fairwater and fairwater planes at varous angles of attack, sideslip, and fairwater plane deflection. The vortex effects are found to be appreciable for normal force pitching moment, and rolling moment at high angles of sideslip and for all forces and moments at combined angles of attack and sideslip. Reference 7 studies similiar vortex effects which are present during steady pitching and steady yawing motion. A particular value of these theoretical studies is the development of a nonlinear hydrodynamic force model structure. The accurate estimation of the parameter values in the model requires expermental data.

Tank Tests (Submarines)

The tests of scale model vehicles can be used to provide some of the data required for the estimation of the parameters required by an accurate submarine dynamic model. This section outlines the capabilities and drawbacks of the commonly used tank testing techniques.

1. Oblique Towing

Oblique towing tests are carried out in order to determine the longitudinal and transverse forces and the yaw moment on the submarine as a function of the speed, angle-of-attack, sideslip angle, control surface angle, and propeller rpm.

Two kinds of tests are performed:

a. static control surface tests, during which forces and moments are measured for zero degree drift angle and several combinations of speed, rpm, and control surface deflection; and
b. static drift angle tests, during which forces and moment are measured for several combinations of speed, angle-of-attack, and sideslip angle, while the control surfaces are kept at 0 degrees and the rpm corresponds to the self-propulsion point of the model.

During these tests the torque of the propeller is measured as well.

2. Rotating Arm

The rotating arm technique is used specifically to detemrine the hydrodynamic derivatives of yawing, but may also be used for the same purpose as the oblique towing tests.

In the rotating arm tests, the model is towed along circular paths at a constant linear speed. The angular velocity is changed by varying the radius of the circle. A dynamometer measures the transverse force and the angular moment acting on the model.

The main drawback of the rotating arm technique is that it cannot be used to detemrine the angular acceleration derivatives. Also, there are some problems associated with its operation, namely:

a. the model must be accelerated and all the measurements taken in one revolution in order to avoid the interference of the model's wake; and
b. in order to perform the tests at a small value of the angular velocity, it is necessary to use a high ratio of the radius of the turn to the model length which frequently requires the use of smaller models which leads to scale effects.

3. Planar Motion

The planar motion mechanism (PMM) tests are carried out with the primary purpose of detemrining the acceleration derivatives (added mass and added moment of inertia coefficients) and some of the cross coupling derivatives, such as the ones involving drift and yaw.

The PMM can be mounted on the carriage of a towing tank. It imparts oscillatory motions to the bow and stern of the model while it is being towed at constant speed. By carefully selecting the phase angle between the bow and stern oscillations, it is possible to establish a motion that is pure yaw, pure sway, or any combination of the two.

During the PMM tests, the rudder angle is set at zero degrees and the propeller rpm is adjusted in accordance with the self propulsion point of the model. The test data, being cyclic are affected by:

a. tank resonance - a function of tank dimensions and test frequency,
b. free surface waves generated by a model near the surface - a function of the speed and test frequency, and
c. unsteady lift or memory-effects.

4. Horizontal Oscillation Techniques

The oscillation technique differs from the PPM in that only one oscillator is used to oscillate the model in yaw about any selected origin while that origin is towed in a straight line along the towing tank.

The motions of the model during the tests are always a combination of rotation and translation. Hence, the forces and moments measured during the oscillations are a mixture of static, rotary and acceleration components. In order to determine the rotary and acceleration derivatives, it is necessary to know before hand the static force and moment derivatives. The forces and moments are measured for the model oscillated about two different locations of the origin, and the unknown hydrodynamic derivatives are then determined by the solution of a system of simultaneous equations.

The biggest drawback of the oscillator techniques is the possiblity of introducing considerable errors in the solution of the simultaneous equations because of the wide difference in magnitude between the individual derivatives. Therefore, the results of the oscillator type of tests are not usually considered as accurate as those obtained from the PPM.

Table 1 summarizes the use of the above test methods. All of the tank test methods described in Table 1 contain several disadvantages. The primary problems are scale effects. In general, the parameters in the hydrodynamic force and moment relations vary as a function of the relevant dimensionless parameters such as Reynolds, Froude, or Strouhal. At present, it is impossible to determine these functions exactly. Also, the towing tank walls and bottom modify the flowfield around the ship model. The rotating arm technique suffers additionally by requiring a very large facility.

Tank testing methods have another drawback unrelated to scale factor or wall effect. Namely, the tests do not provide information for model structure determination. All of these tests also depend upon inducing special motions while restricting others in order to isolate the effects of various stability derivatives or possible nonlinear terms. The experimenter can only estimate the values of parameters relating to hydrodynamic effects whose existence is suspected *a priori*. For definitive hydrodynamic force model structure determination, another technique, such as free running scale model experiments or full scale trials, is essential.

Free Running Model Tests

The effects of tank walls and of *a priori* model structure misconseptions can be eliminated by using data from free running vehicle tests. Scale effects can only be eliminated by using the actual vehicle in full scale trials. However, full scale trials presents its own set of difficulties. First, the environment in which the vehicle operates is not precisely controlled as in the case with tank tests. Random process disturbances such as waves and water currents can effect the results in ways which are difficult to isolate and quantify. These factors effect repeatability and in addition, full scale trials rarely repeat test maneuvers.

The free running model, however, can eliminate the problems encountered in full scale trials and provide repeatable results. Experiments can be conducted in a completely controlled environment, such as DTNSRDC's maneuvering basin, free from the effects of random disturbances. Test maneuvers can be repeated as many times as necessary to determine the

variance of the results. Therefore, the free running model can be successfully used to eliminate the effects of tank walls and of a priori model structure misconseptions while also eliminating the problems associated with full scale trials.

The only significant problems with obtaining useful information from free running vehicle tests is that the data processing following the experiment is anything but straightforward. In general, the data recorded by each of the instruments in the experiment will be a function of all of the parameters of interest. The isolation of the effects of individual parameters, the goal of tank test techniques such as oblique towing, is usually not possible.

REVIEW OF METHODS OF SUBMARINE TEST DATA ANALYSIS

One advanced method that has been developed and successfully applied to real data is an implementation of the maximum likelihood criterion. This numerical algorithm is discussed in Reference 10. It is a combination of three steps: (1) extended Kalman filter to estimate the states and generate a residual sequence, (2) modified Newton-Raphson algorithm for the parameter estimates, and (3) an alogorithm to estimate the noise statistics (means and variances of the measurement and process noise).

Reference 11 developes a method for estimating the parameters in a nonlinear submarine dynamics model which is very similar to NSRDC Report 2510. The authors use a least squares equation error approach. A significant problem with the equation error method is that the algorithm requires measurements or estimates of all of the submarine dynamic states and state time derivatives. Reference 11 assumes that measurements of all of these quantities will be available. The problem of estimating missing states or state time derivatives form incomplete (in the sense that not all states are measured) and noisy data is not treated. Also, no method of model structure determination using the experimental data is considered.

Reference 10 developes a "force and moment identification technique". This technique computes force and moment time histories which cause agreement between a simulated submarine maneuver and a set of data from an actual maneuver. The difficulty here is that producing such agreement by itself has little predictive capability. The nature of the results precludes their use for predicting the behavior of the submarine in a maneuver which differs even slightly from the one originally analyzed. The step which should follow the force and moment identification is the determination of a structure for representing the "add-on" forces and moments as a function of the submarine states. Then the simulation should be modified and used to predict a number of trajectories over the range of variables for which the over-all process applies.

Reference 13 demonstrates the use of extended Kalman filter methods to identify nonlinear lateral ship dynamics models using simulated data. This report considers the effect of various input time histories on the identifiability of the linear and nonlinear parameters. Small amplitude inputs are found to be better for estimating linear parameters while large amplitude inputs are better for nonlinear parameters.

References 14 and 15 develop two system identification methods and apply them to undersea vehicle system identification. The first method is a generalized least squares technique for parameter estimation in a linear constant-coefficient discrete-time system. The second method is a nonlinear system identification method which blends the equation error and output error formulation in order to obtain the unbiased estimation characteristics of the latter formulation without directly requiring a priori parameter estimates. The algorithms are used on data from experments with the Deep Submergence Rescue Vehicle and from a towed sonar vehicle.

System identification techniques have been applied in the past to the problem of determining dynamic models of both surface ships and submarine vehicles. Best known is the application of maximum likelihood

methods by reference 16 to determine models of the lateral dynamics of surface ships. The models used are second and third order linear dynamic systems which relate rudder angle to heading angle. The models include both random measurement and process noise sources. The data are from experiments carried out aboard a 15,000 ton freighter and a 255,000 ton tanker. The authors use an F-test described by reference 17 to determine the best model order. At this time the important validation step of comparing models obtained form one set of experiments against data from another experiment has not been done.

THE ROLE OF SYSTEM IDENTIFICATION

The role of system identification in vehicle dynamic modeling must be defined in the light of the purpose of such modeling and the available techniques for gathering data and postulating model structure. The unique potential contributions of system identification to submarine modeling can be summarized as follows:

(1) Validation. Vehicle hydrodynamic models can be determined using tank testing and theoretical analysis. However, complete confidence in the results of these methods is not possible until the resulting models can predict the behavior of full scale, free running vehicles. It is doubtful that the theoretical or empirical models will yield perfect agreement initially with full scale trial results. The development of models from full scale test data using system identification can isolate and quantify the deficiencies of the *a priori* models.

(2) Estimation of Unsteady Hydrodynamic Effects. The hydrodynamic forces and moments acting on the vehicle depend on unsteady hydrodynamic effects. These effects are difficult to treat analytically. It is also difficult to measure these effects using tank testing methods due to nonlinearity and tank resonance effects. The detailed quantitative analysis of full scale data may be essential to an understanding of unsteady hydrodynamic effects.

(3) Isolation of Cross Coupling Effects. The lateral and longitudinal motions of a vehicle are coupled hydrodynamically in complex ways. A complete study of all of the possible cross coupling mechanisms using tank testing suffers from the "curse of dimensionality". Even the determination of quasi-static hydrodynamic effects requires tank testing of a large number of combinations of various attitudes and angular rates. A relatively small number of free running maneuvers may be able to excite most of the nonlinear cross coupling effects. System identification techniques could determine a model for the cross coupling effects by processing data from these tests.

(4) Determination of Model Structure. Perhaps the strongest argument for free running model tests, and the subsequent processing of data using system identification, is that it can give the analyst or experimenter information on phenomena whose presence is not known, or at least only suspected. The significance of previously neglected phenomena should be revealed by the inability of system identification techniques to match free running test data using *a priori* model structures. The determination of a satisfactory model structure with accurate parameter estimates will also require insight into a large range of hydrodynamic phenomena together with data processing techniques capable of efficiently extracting the maximum information from the available data.

CONCLUSIONS AND RECOMMENDATIONS

Tank tests and theoretical analysis can determine some parameters and a candidate structure for a submarine hydrodynamics model. The roll of system identification is to process the data from free running full scale and model tests to validate parameter estimates and to assess the adequacy of the model structure.

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RECOMMENDATIONS

The system identification techniques, while not a panacea that will solve all modeling problems, does show sufficient promise to warrent further investigation. Further, its use in a coordinated manner along with the more conventional towing tank techniques offers the possibility for significant improvements in marine vehicle modeling.

Accordingly it is recommended that a captive model - free running model - system identification based research program be vigorously pursued.

SHIP MANEUVERING CHARACTERISTICS IN DEEP AND SHALLOW WATER
(Applications of Captive Model Test Results)

by

HARUZO EDA
Davidson Laboratory
Stevens Institute of Technology

INTRODUCTION

During the past few years, analytical and experimental studies on shallow water maneuvering characteristics have been continued with a major emphasis placed on dynamic behavior of ships (in particular VLCCs) in waterways and harbors.[1-9]

This report will review recent model test data in deep and shallow water, which have been obtained at Davidson Laboratory, and will also present the application of the model test data to ship motion simulations.

The following ship models have recently been tested under the rotating-arm facility in deep and shallow water:

1. A 763-ft-long 80,000 DWT tanker, which is a representative medium size tanker.
2. A 1085-ft-long 250,000 DWT tanker, which is a representative VLCC.
3. A 1066-ft-long 280,000 DWT tanker, which was recently tested under the shallow-water, full-scale trial program in the Gulf of Mexico.
4. An 880-ft-long high-speed container ship (i.e., the SeaLand 7-type design).

The above-mentioned shallow-water, full-scale trials were carried out from July 25 through August 4, 1977, under the sponsorship of the U.S. Coast Guard, MARAD, and AIMS. The trial results provide an opportunity to correlate ship motion predictions based on the model test data with trial results in shallow water as well as in deep water.

ROTATING-ARM TEST RESULTS

Figure 1 shows an 80,000 DWT tanker-model (1/150 scale) set up in shallow water ($D_W/H=1.2$) in the rotating-arm facility. Tests were made with freedom in heave and trim, but restrained in yaw, roll, sway, and surge. Balances mounted above the model were used to measure longitudinal and side forces, and yaw moment. Signals from transducers were transmitted by overhead cables to the calibrated standard recording equipment on shore. The 64-ft-long rotating arm is located in a 75-ft-long by 75-ft-wide by 5-ft-deep tank.

The major parameter changes during a series of tests were, for example, as follows:

(1)	loading condition	full-load and ballast conditions
(2)	water depth	$D_W/H = \infty, 1.5, 1.2, 1.1$

(3) model speed F_n = 0.04, 0.08, 0.16, 0.30

(4) turning rate r' = -0.80 to +0.80

(5) drift angle β = -25 deg to +25 deg

(6) rudder angle δ = -40 deg to +40 deg

(7) propeller revolution various propeller loading conditions, including model and ship self-propulsion points

In order to obtain hydrodynamic data which represent realistic dynamic response characteristics of a given ship, effects of the above parameters on hydrodynamic forces should be determined through a series of tests. A total number of test runs for one ship model is usually up to the order of several hundreds.

Figures 2 and 3, for example, show hydrodynamic yaw moment data points which are computer-plotted on the basis of drift angle together with least-square fitted curves in deep and shallow waters (depth to draft ratio, D_W/H = 17.0 and 1.2), respectively. A significant difference in hydrodynamic yaw moment is clearly shown between deep and shallow water in these two figures. Hydrodynamic sway force indicated a similar difference in a more exaggerated manner.

Figure 4 shows changes in hydrodynamic force and moment derivatives (Y'_v and N'_v) with $\sigma(=H/D_W)$, which indicate a much larger change in Y'_v with σ than in N'_v. Various hydrodynamic force and moment derivatives change substantially with σ in a fairly similar manner but to a different degree. As a result, the dynamic course stability and turning characteristics of the ship change to a great extent with changes in water depth. When water depth is reduced from deep to very shallow water (e.g., D_W/H = 17 to 1.2), the following changes in stability and maneuvering characteristics were indicated in the test results:

(1) Dynamic course stability is increased with reduction in water depth.

(2) Turning performance is decreased with reduction in water depth.

It should be noted that maneuvering requirements are more severe in restricted shallow water rather than in open deep water. Accordingly, the above changes in maneuvering characteristics with a reduction in water depth are very important, in particular, from the viewpoint of navigational safety.

DYNAMIC BEHAVIOR OF TANKERS DURING TRANSIT OF HARBOR WATERWAYS

Recently, a study was undertaken at Davidson Laboratory to examine the dynamic behavior of tankers proceeding through harbor waterways from open sea. The controllability of typical 250,000 DWT and 80,000 DWT tankers was to be evaluated under the conditions of expected tide, currents and wind,and with the specific configuration of that channel and the surrounding water and land. The system performance was to be expressed in terms of the ship trajectory deviation relative to the ideal track and the amount of rudder activity.

A mathematical model was formulated with inclusion of the following data:

(a) Hydrodynamic force coefficients on the basis of hydrodynamic data obtained in the rotating-arm facility in deep and shallow water.

(b) Aerodynamic force coefficients on the basis of wind tunnel data.

(c) Actual current pattern in waterways.

(d) CGS chart data on the waterway configurations and water depths.

The mathematical model to represent the tankers dynamic response was previously verified with full-scale ship trial results in the case of deep water.[7]

As the ship proceeds along the channel, changes in water depth were reflected in the values of hydrodynamic coefficients, thereby effecting the ship maneuvering characteristics.

Pilot feedback control was represented in the following rudder activity, which is based on deviations in ship heading and distance of the ship from the desired track.

$$\delta_d = a(\psi_s - \psi_c) + b'\psi_s' + c'\ell_p'$$

where

δ_d = rudder command

ψ_s = ship heading angle

ψ_c = channel direction

ℓ_p' = distance between the ship and the desired track in terms of ship length

a,b',c'= gain constants

Anticipatory control in negotiating turns in the waterway was included in the mathematical model. When the ship approached the bend, rudder action started prior to reaching the actual location.

Results of computer-simulation under various wind and current conditions were obtained on computer-plotted charts, each of which gives the computed ship trajectory relative to the desired track. Figures 5 to 8 show typical examples of computation results for the 250,000 DWT tanker and the 80,000 DWT tanker under the influence of wind and current.

Figure 9 shows recently measured trajectory of the 80,000 DWT tanker entering the Upper New York Bay under the Verrazano Narrows Bridge. Recorded data included rudder and bow-thruster activity, and propeller revolutions. It is planned to correlate such a full-scale trajectory with computer simulations using model test results in shallow water.

APPLICATION OF HYDRODYNAMIC DATA TO SHIPHANDLING SIMULATORS

Significant progress has been made in the area of shiphandling simulators during the past several years. Two advanced simulators have recently been completed and are presently in operation. These are the MARAD CAORF simulator at Kings Point and the Marine Safety International simulator at LaGuardia Airport (see Figures 10 and 11). Recent experiments and training programs on these simulators include,

1. the 80,000 DWT tanker entering New York Harbor,

2. the 165,000 DWT tanker leaving Port Valdez, Alaska,

3. the 250,000 DWT tanker entering Milford Heaven, U.K.,

where hydrodynamic data, determined from captive model tests and hydrodynamic theories, play an important role in these simulator operations to generate realistic dynamic response of these ships in deep and shallow water.

CONCLUDING REMARKS

Recent captive model test data in deep and shallow water have been reviewed in this report with inclusion of their actual

application to ship motion simulators.

Results clearly indicate significant changes in course stability and maneuvering characteristics with reduction in water depth. The changes due to shallow water depth are particularly important because maneuvering requirements are generally more severe in shallow waterways rather than in open deep water. Under the current research programs, Davidson Laboratory is presently scheduled to continue its efforts in the following areas:

1. Extend the captive model tests for several additional designs (e.g., one of the largest ULCCs).

2. Analyze the test data to be used in ship motion predictions, and develop maneuvering criteria in deep and shallow water.

3. Correlate ship trajectories between full-scale trials and predictions in deep and shallow water.

The correlation between ship trial data and predictions will include the case of the 280,000 DWT tanker in deep and shallow water and also the case of smaller size ships entering actual harbors (e.g., New York Harbor), with inclusion of varying water depth and current.

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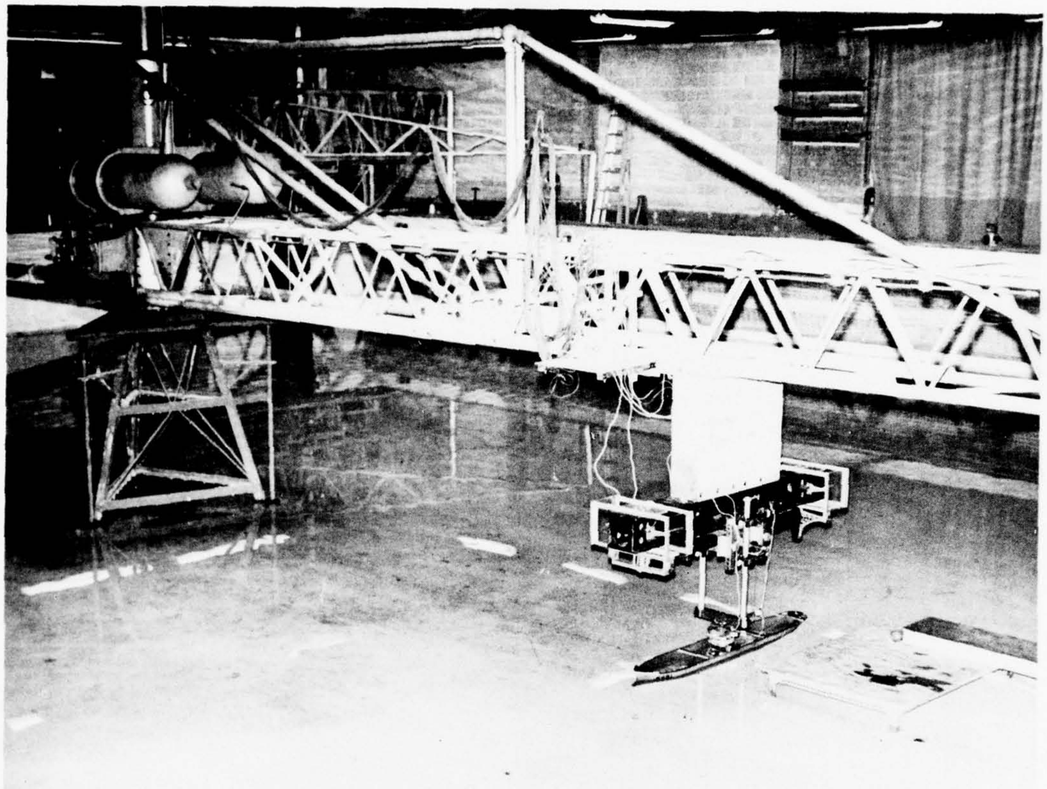

FIGURE 1. THE 80,000 DWT TANKER MODEL BEING TESTED IN SHALLOW WATER IN THE ROTATING-ARM FACILITY.

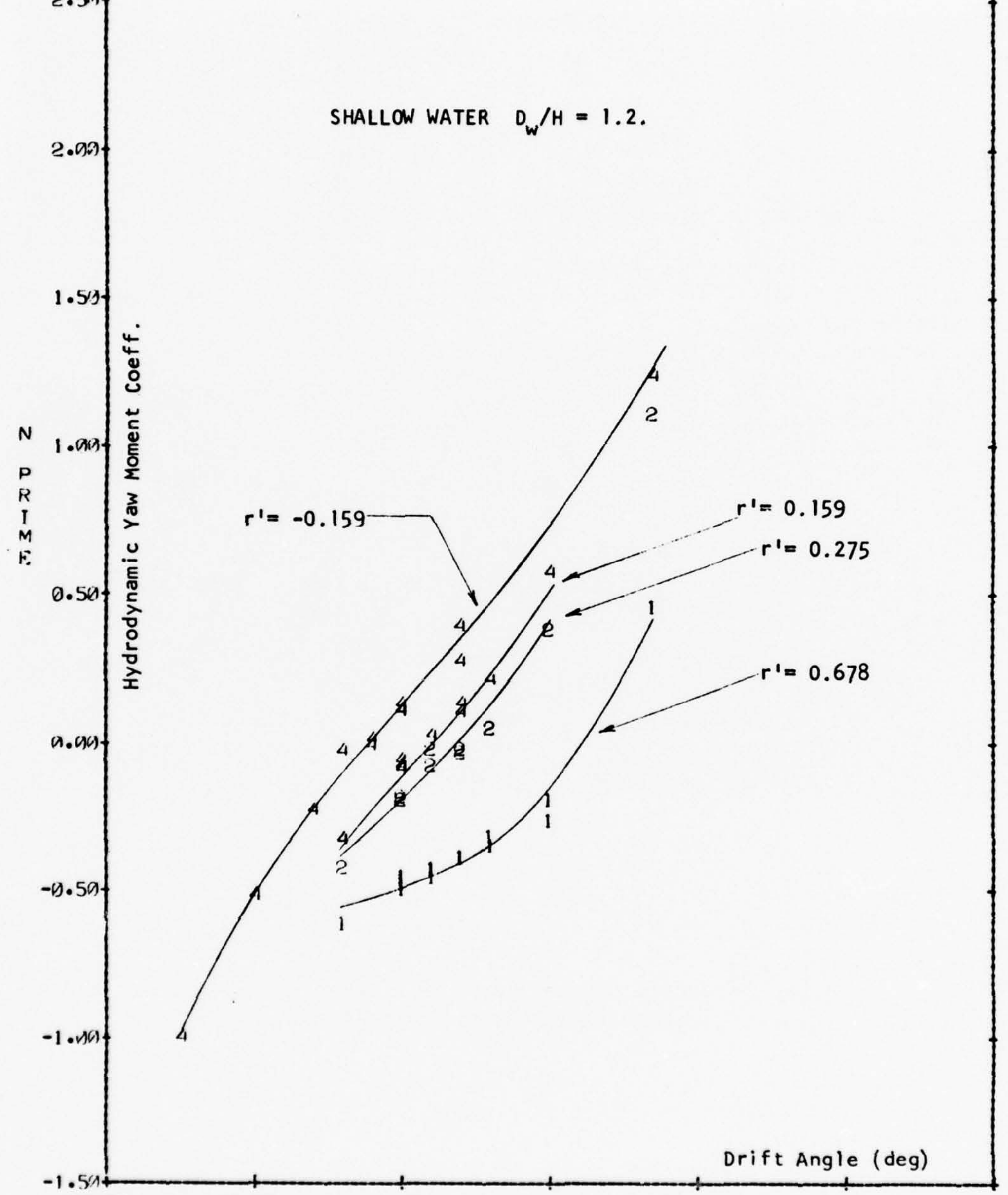

FIGURE 2. HYDRODYNAMIC YAW MOMENT VERSUS DRIFT ANGLE

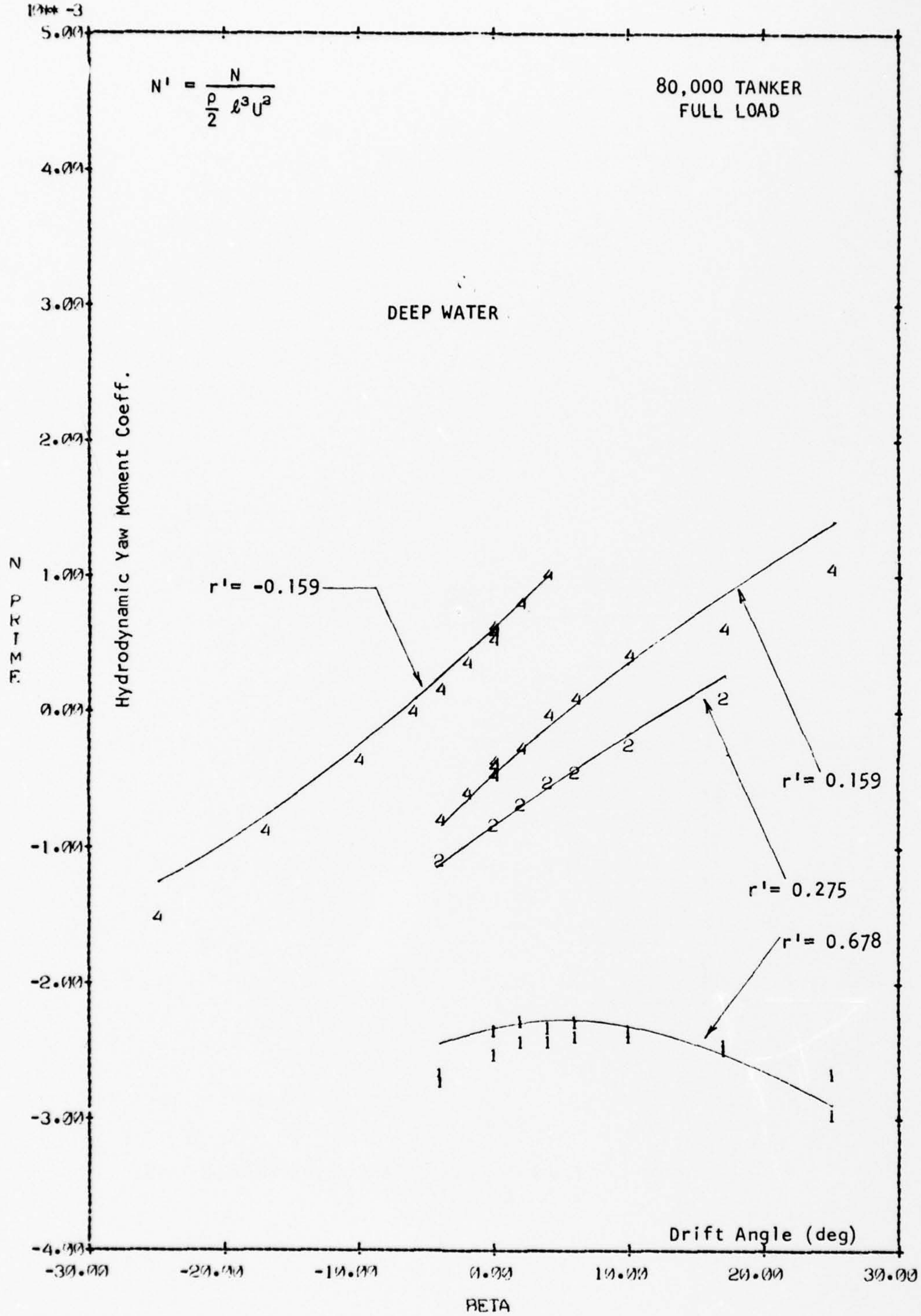

FIGURE 3. HYDRODYNAMIC YAW MOMENT VERSUS DRIFT ANGLE

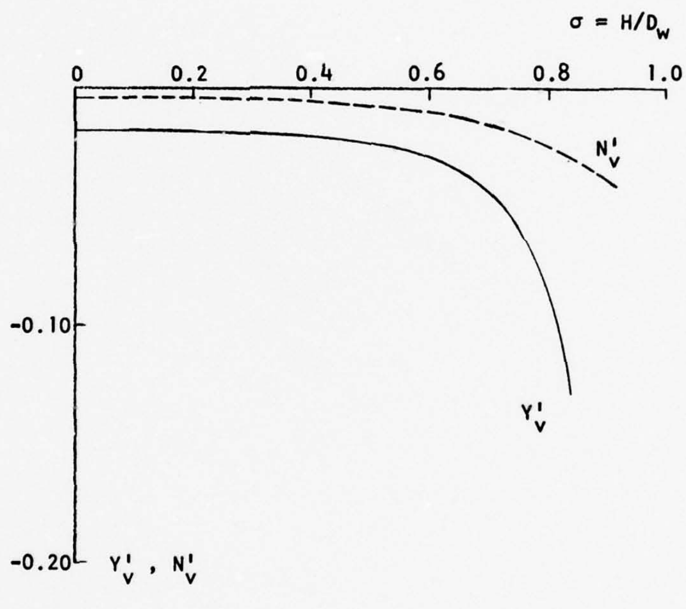

FIGURE 4. CHANGES IN FORCE AND MOMENT DERIVATIVES WITH WATER DEPTH.

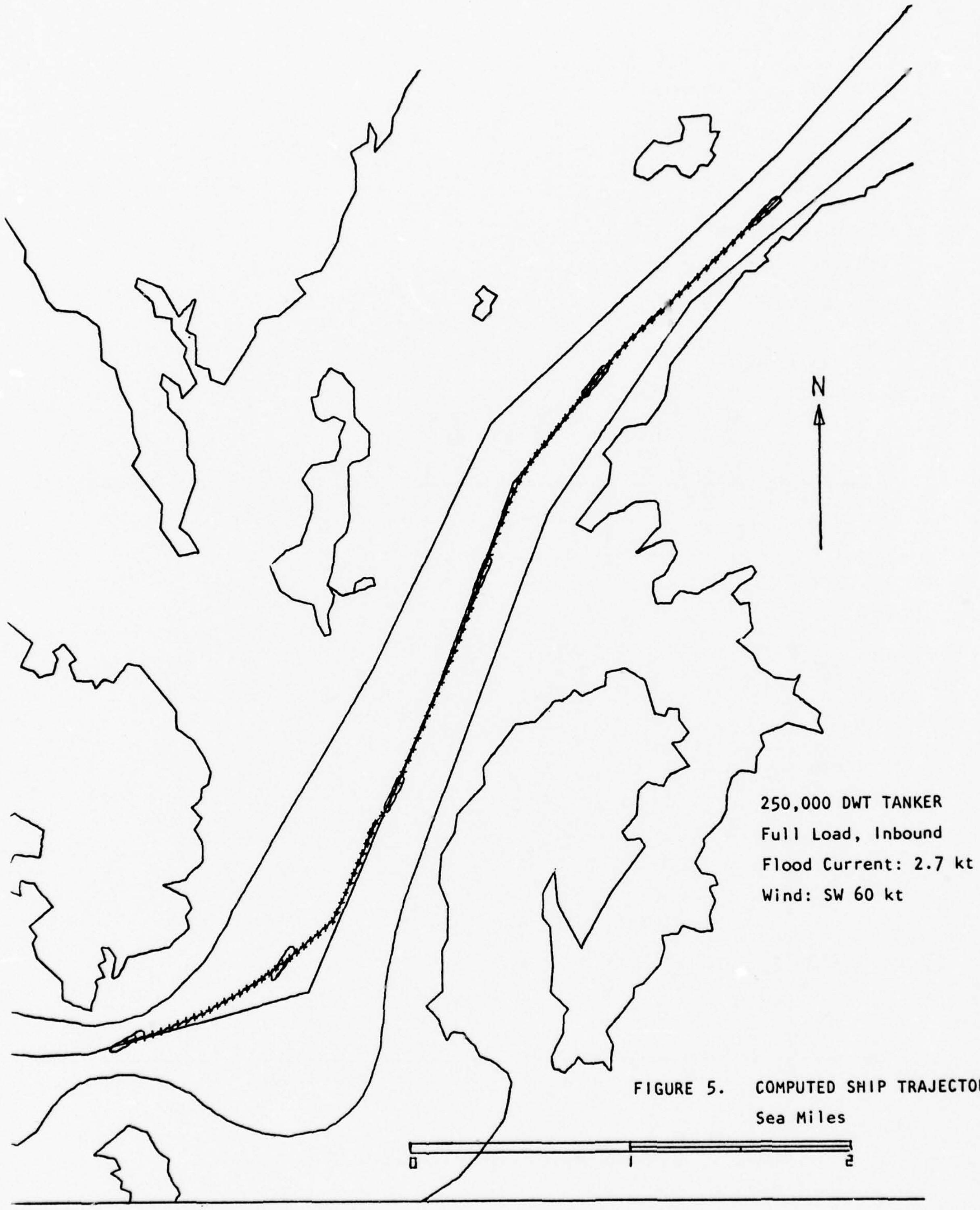

FIGURE 5. COMPUTED SHIP TRAJECTORY
Sea Miles

250,000 DWT TANKER

Full Load, Inbound
Flood Current: 2.7 kt
Wind: SW 60 kt

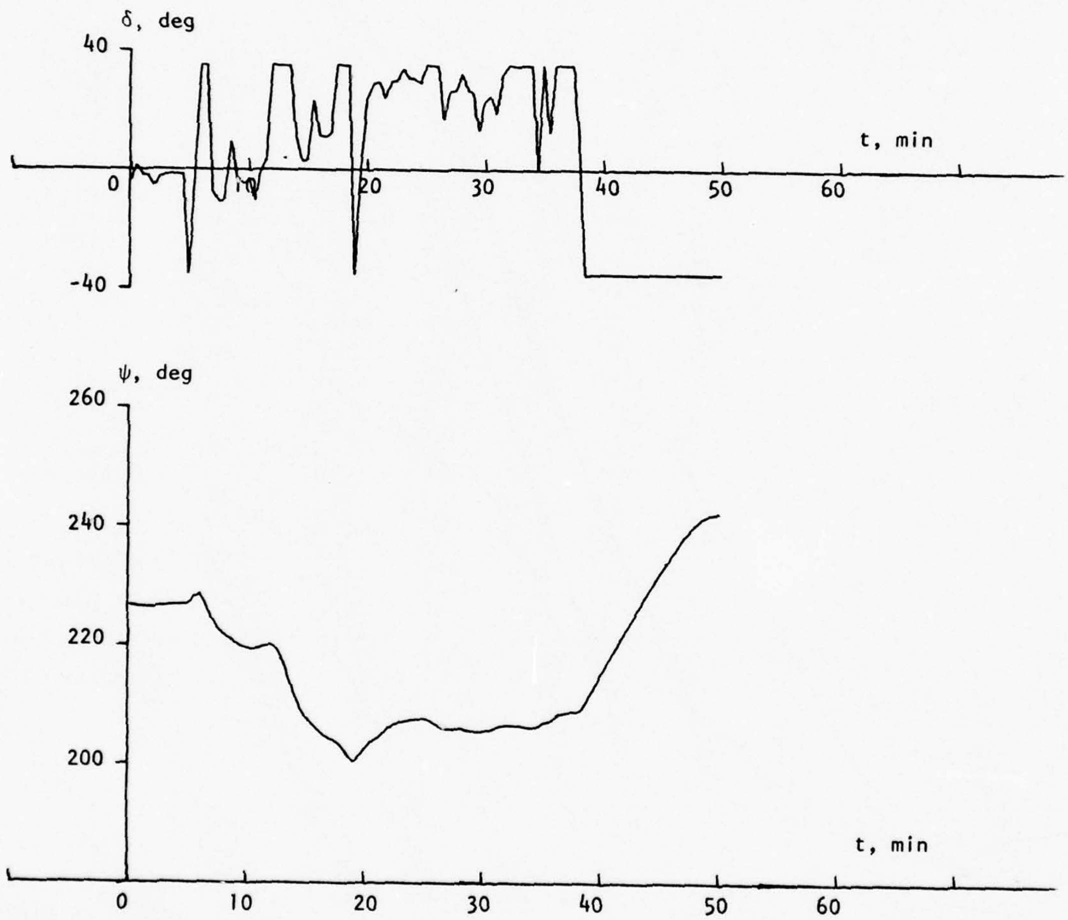

FIGURE 6. COMPUTED RUDDER ANGLE $\delta(t)$ AND HEADING ANGLE $\psi(t)$

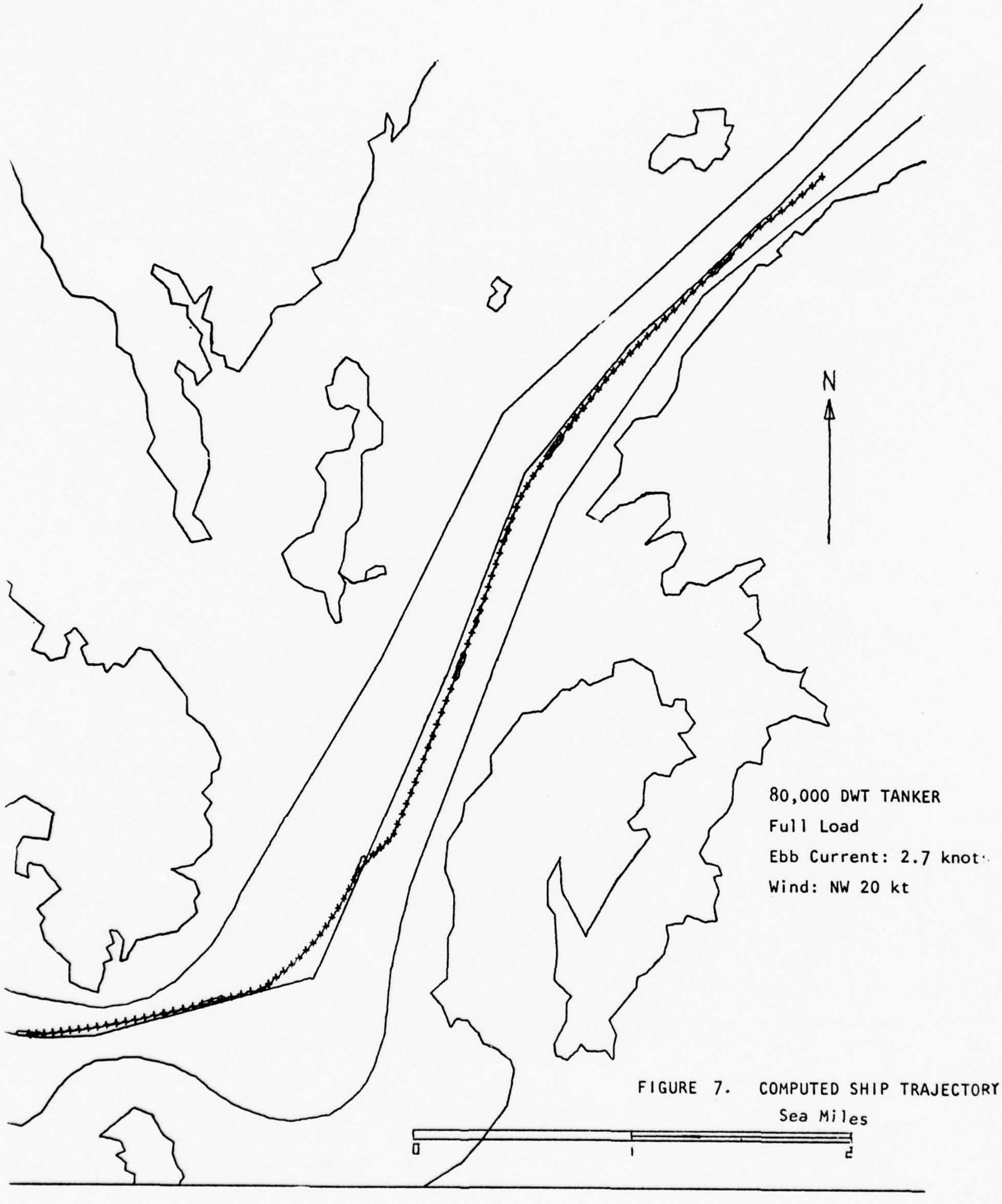

FIGURE 7. COMPUTED SHIP TRAJECTORY

80,000 DWT TANKER

Full Load
Ebb Current: 2.7 kt
Wind: NW 20 kt

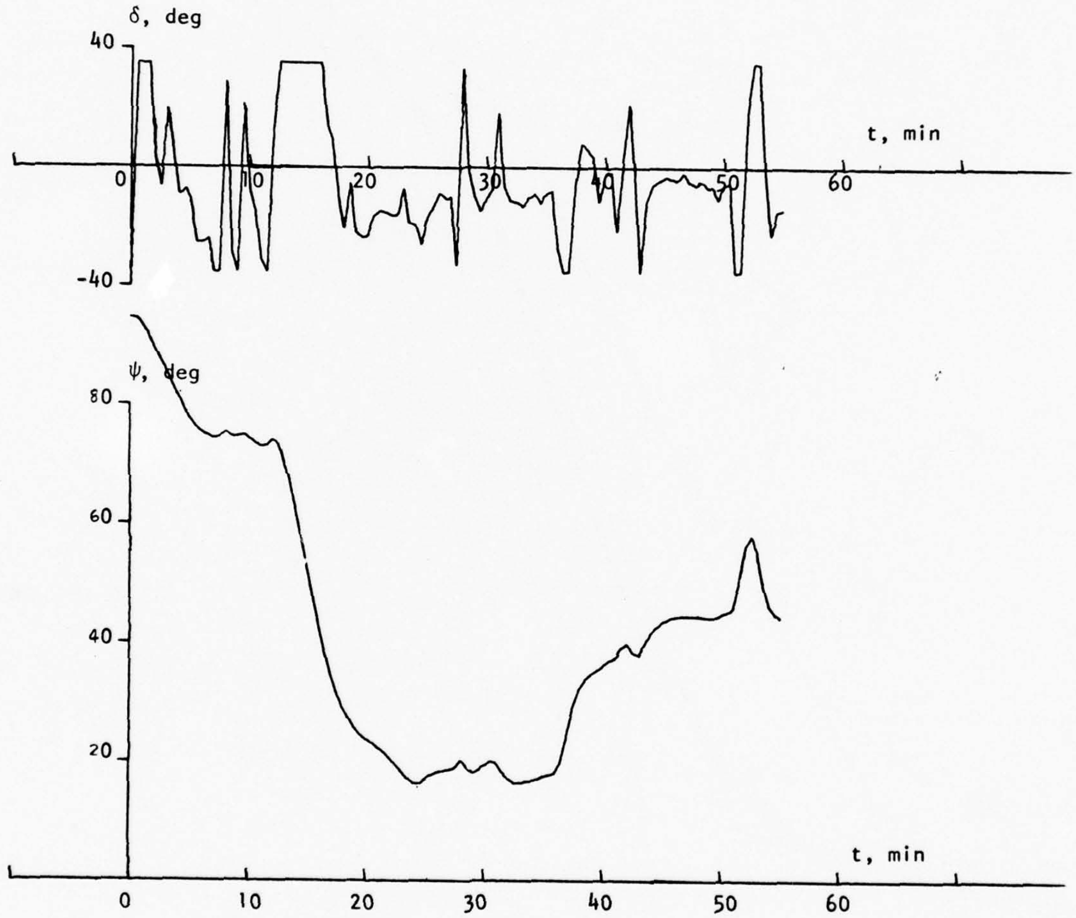

FIGURE 8. COMPUTED RUDDER ANGLE δ(t) AND HEADING ANGLE ψ(t)

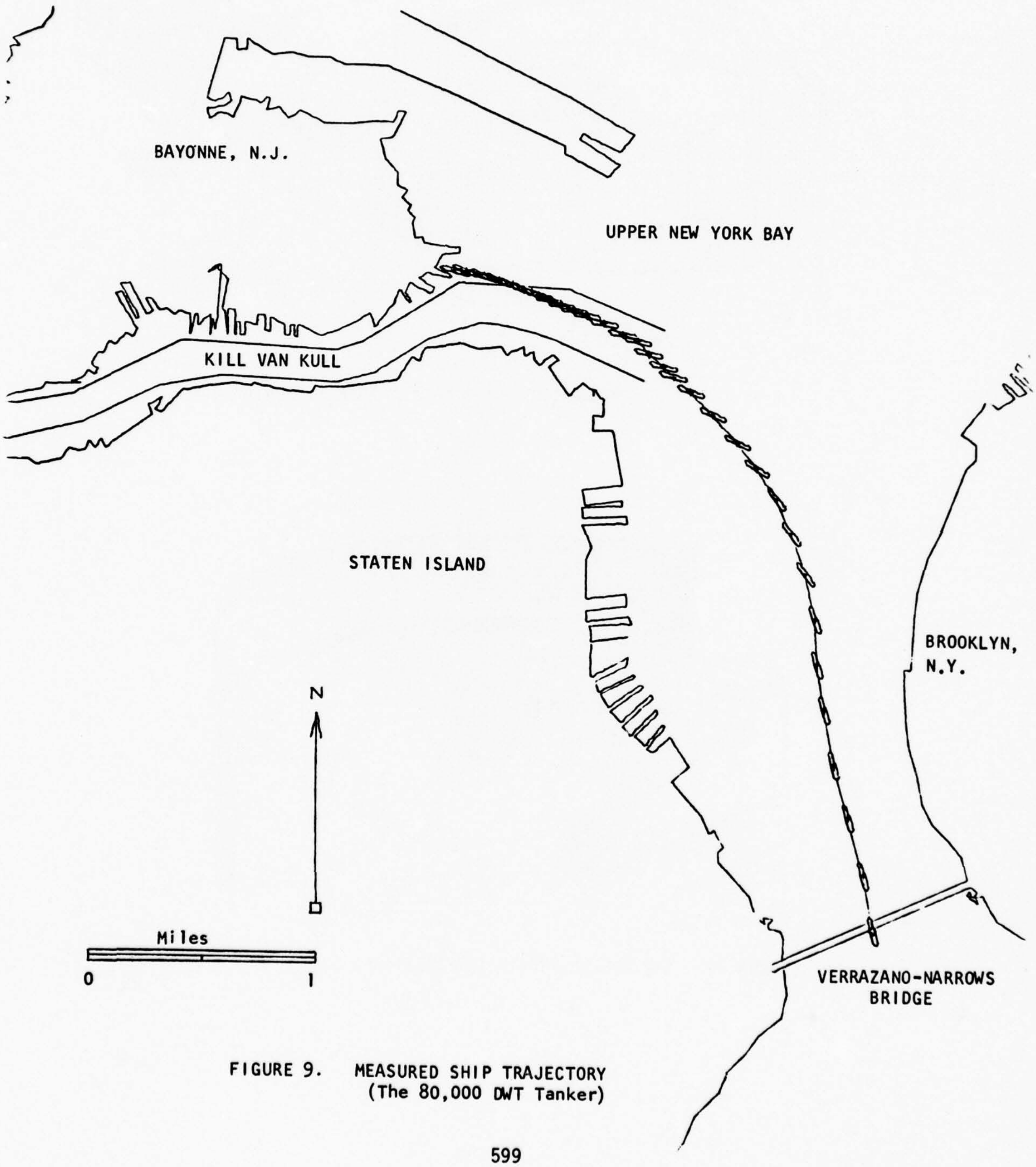

FIGURE 9. MEASURED SHIP TRAJECTORY
(The 80,000 DWT Tanker)

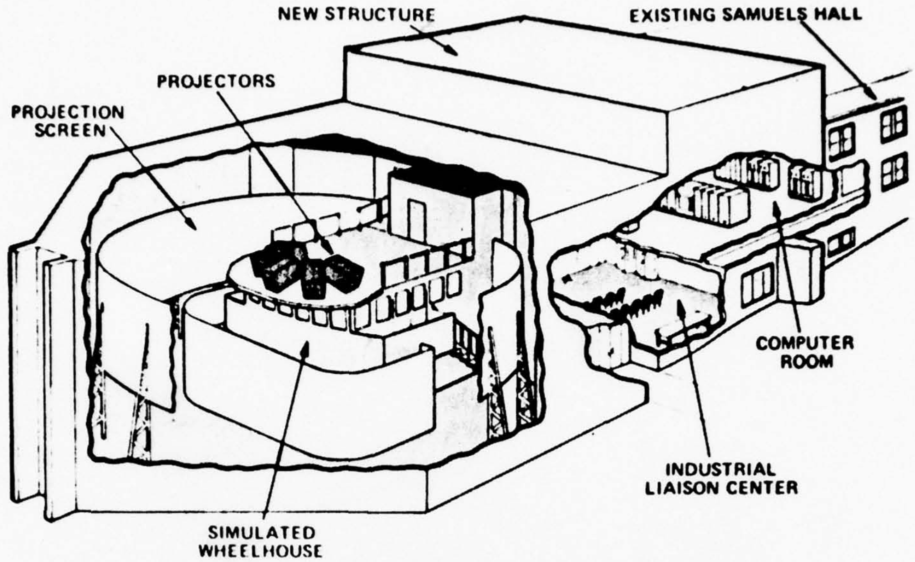

FIGURE 10. THE MARAD CAORF SIMULATOR

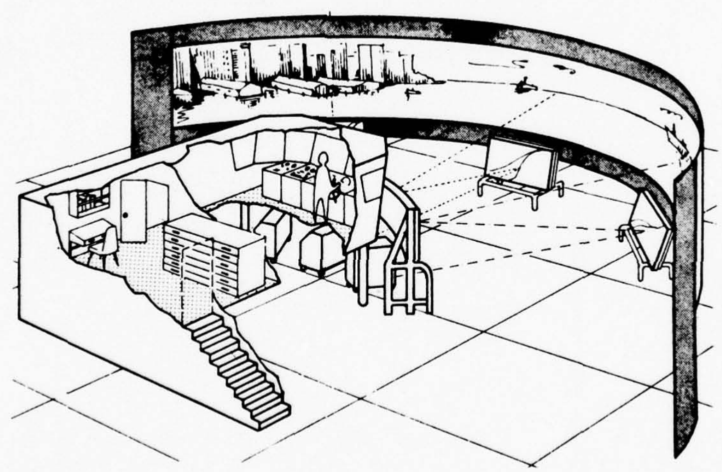

FIGURE 11. THE MARINE SAFETY INTERNATIONAL SHIPHANDLING SIMULATOR

THE APPLICATION OF ROTATING ARM DATA
TO THE PREDICTION OF ADVANCED SHIP
MANEUVERING CHARACTERISTICS

Steering and Maneuvering

James A. Fein
David W. Taylor Naval Ship
Research and Development Center

18th American Towing Tank Conference
U. S. Naval Academy
Annapolis, Maryland
August 1977

Advanced ship types such as Air Cushion Vehicles (ACV's) and Small Waterplane Area Twin Hulls (SWATH's) can present difficult maneuvering problems to the designer. These ships differ greatly from traditional ships in degree of stability and in the nature of the steering control strategies. The forces and moments involved in turning are highly dependent on speed since these ship types operate at Froude numbers in the neighborhood of the wave drag hump. The rotating arm at the David W. Taylor Naval Ship Research and Development Center (DTNSRDC) has been utilized to obtain nonlinear side force, yaw moment and roll moment data for use in a simulation of the JEFF(A) and (B) designs for an air-cushion-supported Amphibious Assault Landing Craft (AALC). This simulation also incorporated straight-line and Planar Motion Mechanism (PMM) information. The forces and moments required by the simulation model are obtained by a table look-up and interpolation technique in place of the traditional technique of using a matrix of coefficient values. Utilizing what was learned from the ACV experiments, a technique that depends totally on the rotating arm for the turning force and moment data was employed in studies of two SWATH designs. This paper discusses the SWATH experiments from which it is established that the rotating arm data is consistent and in agreement with straight-line data from earlier experiments. Simulation results are given and compared with full scale trials results for one SWATH design.

Background

The current approach to determining the maneuvering characteristics of ship designs is to obtain coefficients by PMM or rotating arm experiments and incorporate these coefficients in a simulation program such as that in Reference 1. The PMM approach leads to the acceleration terms but is limited in that the form of the coefficients is dictated by the experimental procedure. Nonlinearities in yaw rate terms are ignored and couplings between yaw rate and roll angle or rudder angle are

restricted to those obtained by oscillating with a fixed angular deflection. Frequency dependence of the forces is assumed to be small or nonexistent. Also, the effects of asymmetrical propulsion cannot be considered.

The rotating arm technique requires that the acceleration terms be known from other sources. The approach can also be limited by the speed or yaw rate capability of the facility. The DTNSRDC rotating arm has a maximum test radius of 114 feet and a maximum speed at the outer end of over 50 knots which allows for a wide range of test conditions. Also a straight-line tank experiment has been required to obtain the sway-velocity derivatives, increasing the accompanying cost.

More recently, techniques have been proposed that depend on complex data analysis. The approach of Reference 2, which describes a force pulse captive model technique, holds promise for quick determination of the acceleration derivatives but does not address the nonlinear derivatives found in most maneuvering work.

ACV Experiments

The ACV experiments are described in detail in References 3 and 4. Traditional techniques were employed to obtain the information needed to simulate the maneuvering of these high speed aerodynamically-propelled craft. Horizontal PMM experiments and straight-line experiments with variation of speed, roll, drift, and trim were conducted. Also, an extensive rotating arm experimental program was conducted.

The experiments led to an extensive data base over a wide range of operating conditions. The forces showed a high degree of Froude number dependence. Also, variation of force with drift angle over a range of zero to 45 degrees was so nonlinear that even a 5th order polynomial did not provide reasonable representation. The high degree of nonlinearity made it very difficult to represent the data by generally accepted Taylor series coefficients. Consequently, rather than develop a whole series of high order coefficients, it was decided that a data table would be established which would have four dimensions and would contain the forces and moments as functions of speed, yaw rate, sway velocity and roll angle. The data base was sufficiently dense to allow linear interpolation between the points. This data base allowed for the development of an efficient, flexible simulation for each of the AALC designs.

The use of the PMM allowed for comparison of the yaw rate derivatives N'_r and Y'_r between the exact values obtained on the rotating arm and the PMM values extrapolation to zero frequency. Figure 1 shows the result of the comparison of N'_r. The agreement between the two techniques is consistent and adequate over the speed range.

SWATH 6A Experiments

The objective of the SWATH 6A experimental program on the rotating arm was to obtain information on a series of different rudder configurations. The SWATH is inherently very directionally stable so rudder size and turning performance are important considerations for the overall design. In the previous simulation studies of ACV, the major portion of the data came from the rotating arm, but straight-line and PMM results were still required since the craft was highly nonlinear and accurate estimates of the acceleration derivatives were not available. However, since funds were limited on the SWATH 6A project, it was decided to gather as much information as could possibly be obtained from the rotating arm and to use theoretical predictions for the acceleration derivatives. In order to accomplish this, it was necessary to improve the efficiency of the technique and to establish that the extrapolation to zero yaw rate would not introduce errors.

A schematic of the model tow rig used on the rotating arm for the SWATH 6A experimental program is illustrated in Figure 2. The roll gage is isolated by a universal to prevent a drag component from being resolved but well positioned for measuring the large expected roll forces. The experiments were conducted at the ship self-propulsion point although various over and under propulsion points were also obtained to assess the effect of propulsion on the forces. These experiments are described in detail in Reference 5. Figure 2 shows the two surface-piercing rudder types, each of which was evaluated for two drafts. Each case was tested for a matrix of speeds, yaw rates (radii), drift angles, rudder angles, and roll angles.

The greatest gain in efficiency was obtained by modernizing the data acquisition system on the rotating arm. By employing a computer and an automated system, numerous data points at different speeds or drift angles could be obtained during a single pass. The data had to be obtained on a single pass around the arm in order to avoid running into the model's wake. The enhanced data acquisition systems allowed the measurement of about 1100 data points during less than two weeks of 16 hour a day testing which included frequent model changes. The computer removed the tares and nondimensionalized the data between runs.

It was necessary to establish that the data was linear near zero yaw rate so that extrapolations of the roll, drift and rudder angle derivatives could be made with confidence. In the table look-up technique, if the values around zero are known and linearity is assumed, linear interpolations across zero will be accurate. Plots of the data versus yaw rate show a high degree of linearity in the vicinity of zero turn rate. Consequently, linear extrapolation to zero yaw rate was judged sufficiently accurate.

Since the data were fairly linear, it proved convenient to calculate linear derivatives for comparing the various rudder configurations. Figure 3 shows the speed dependence of the yaw rate damping derivative, N'_r. The other derivatives also showed a speed effect as can be seen in Figure 4 which shows the rudder effectiveness term, $N'_{\delta r}$. It is apparent from this figure that the spade rudder at the deep draft was the most effective rudder configuration. This conclusion was borne out by the simulation results.

SSP SWATH Experiments

In order to simulate a design for which full scale trials results were available for validation, a completely different SWATH design, the Stable Semi-Submerged Platform (SSP), was the subject of a rotating arm experiment. A 190-ton work boat which is currently in service at the Naval Undersea Center in Hawaii had been the subject of trials in 1975. The SSP rotating arm experiment was similar to the SWATH 6A rudder study in scope and test equipment. The model utilized had been run in the DTNSRDC straight-line tank in 1971. The straight-line data could be directly compared for this model to verify the linear interpolation procedure. A similar check on the MARINER in Reference 6 showed good agreement. Negative yaw rates (port turns) were investigated as well in order to verify the extrapolation to zero yaw rate. The small asymmetries encountered between port and starboard are attributable to the fact that both props turned in the same direction on both the model and the full scale.

The straight-line and rotating arm results showed good agreement and linear behavior for side force and yaw rate as can be seen in Figure 5 and for yaw moment and rudder angles as shown in Figure 6. This agreement gives confidence that the SWATH 6A results for the rotating arm can be validly extrapolated to the straight-line case.

Predictions for SWATH

The SWATH 6A and the SSP are treated in the same simulation program. Hydrodynamic data is contained in a separate data base for each rudder configuration or different design. The side force, roll moment, yaw moment, and axial force are compiled for the variables speed, sway velocity, roll angle and yaw rate. The required forces and moments for any combination of these variables is obtained by a four-dimensional interpolation scheme. Rudder deflection angle and associated coupling dependencies are contained in a separate math model. Intermediate drafts are handled by interpolating between the two experimental drafts. The propulsion, including controllable-pitch propellers, is modeled separately based on experimental data. The acceleration derivatives are computed from strip theory by an established and validated program (Reference 7). The SWATH maneuvering simulation was first used to design rudders for SWATH

6A. Figure 7 shows the effect of the various rudders on a typical high speed maneuver. The rudder size and performance can be traded off by the designer against increased drag, weight of the actuator, and turning requirements. The simulation can also be used for studying deceleration, acceleration, and directional stability. This program is fully documented in Reference 8.

The SSP simulation was used to generate a trajectory that could be compared to the full scale trials results contained in Reference 9. An example of the correlation is given in Figure 8. The results agree within 10%, which is reasonable considering that the trials were conducted in 2-3 foot waves while the simulation is for calm water only. It is hoped that there will be further trials to expand the validation effort.

Conclusions

The rotating arm has been shown to be a useful tool in developing the data base for maneuvering simulations. In some cases, where derivatives for each speed are linear, the arm can be the sole supplier of hydrodynamic data to the simulation. The arm results for the SSP show no yaw rate dependence on rudder effectiveness or sway velocity terms. The arm results for the ACV's give yaw rate damping derivatives that agree with PMM results. The nonlinear nature of the ACV data and the variation of the SWATH derivatives with speed led to the development of linear interpolation table look-up simulations. The agreement with full scale results establishes this approach to simulation as an accurate predictor of advanced ship maneuverability characteristics.

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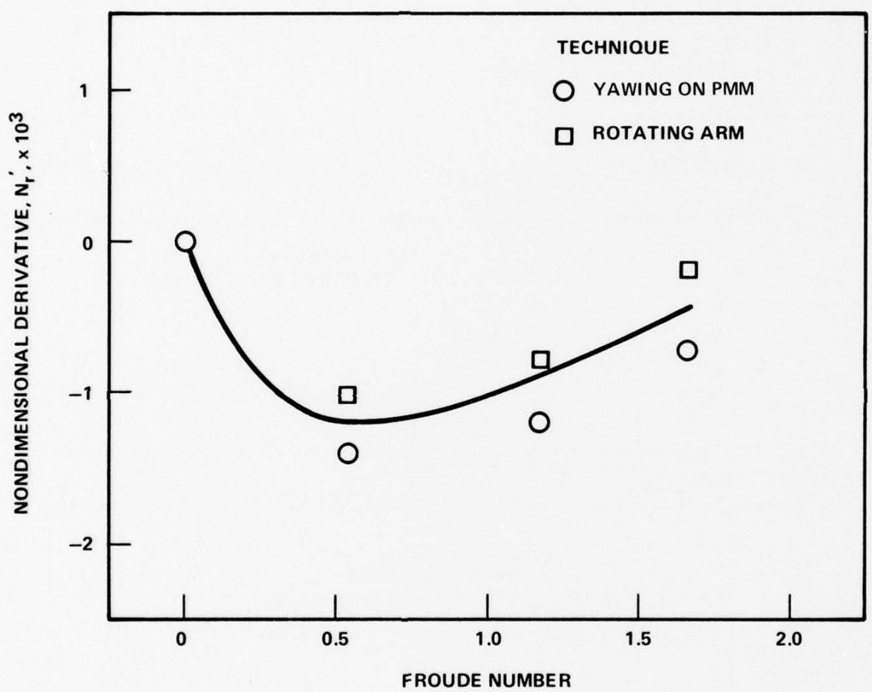

Figure 1 - Variation of Nondimensional Yaw Damping Derivative N_r' with Froude Number as Determined by Two Experimental Techniques on the JEFF(B) AALC

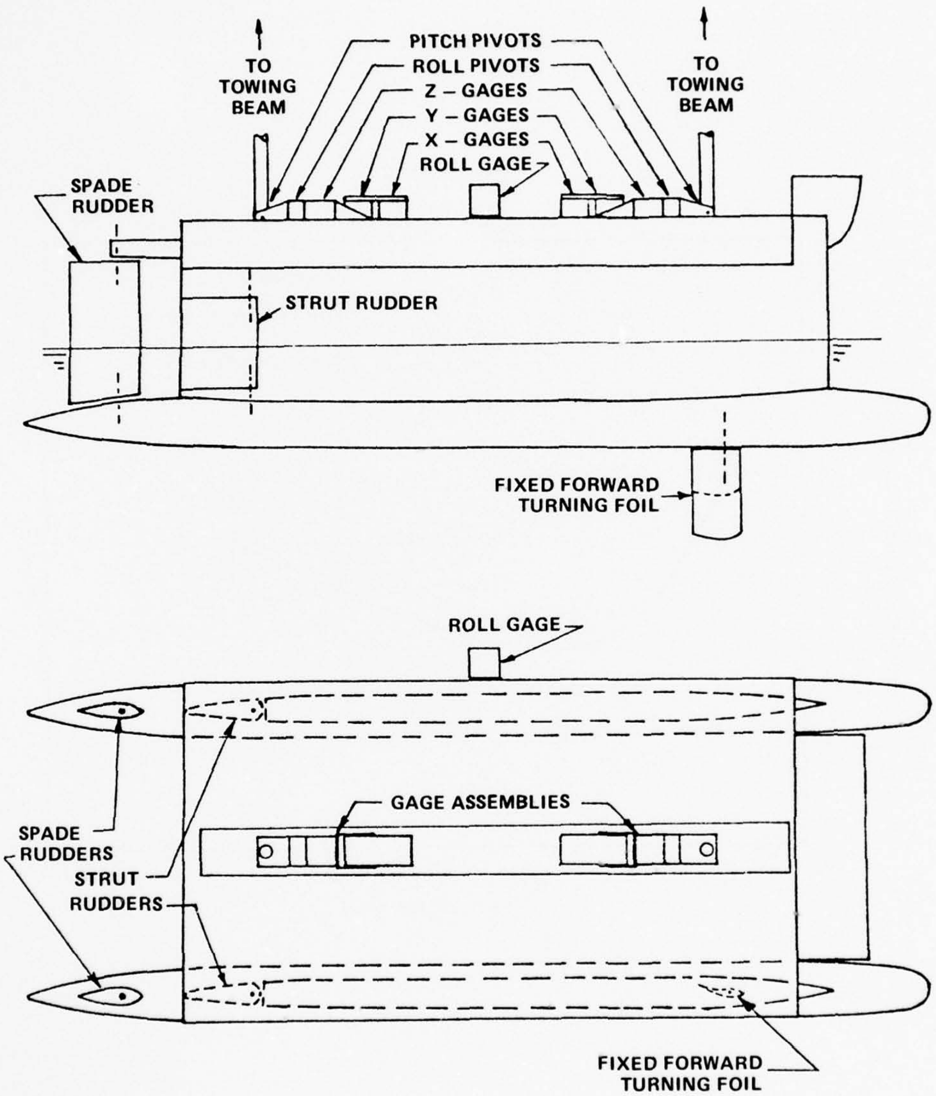

Figure 2 - Schematic for the SWATH 6A Model Showing Locations of the Three Rudders Tested

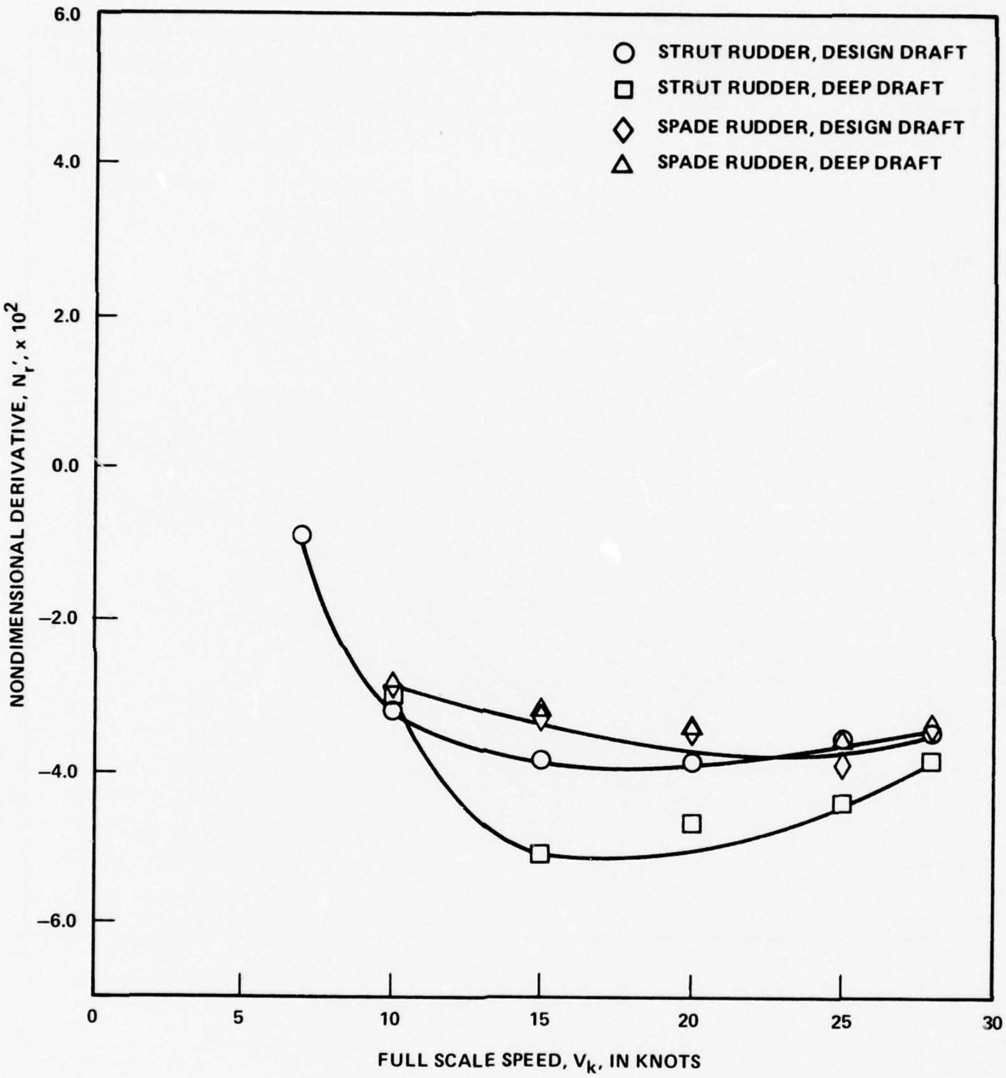

Figure 3 - Variation of Nondimensional Derivative, N_r', for the SWATH 6A, Full Scale Speed for a Series of Rudder and Draft Configurations

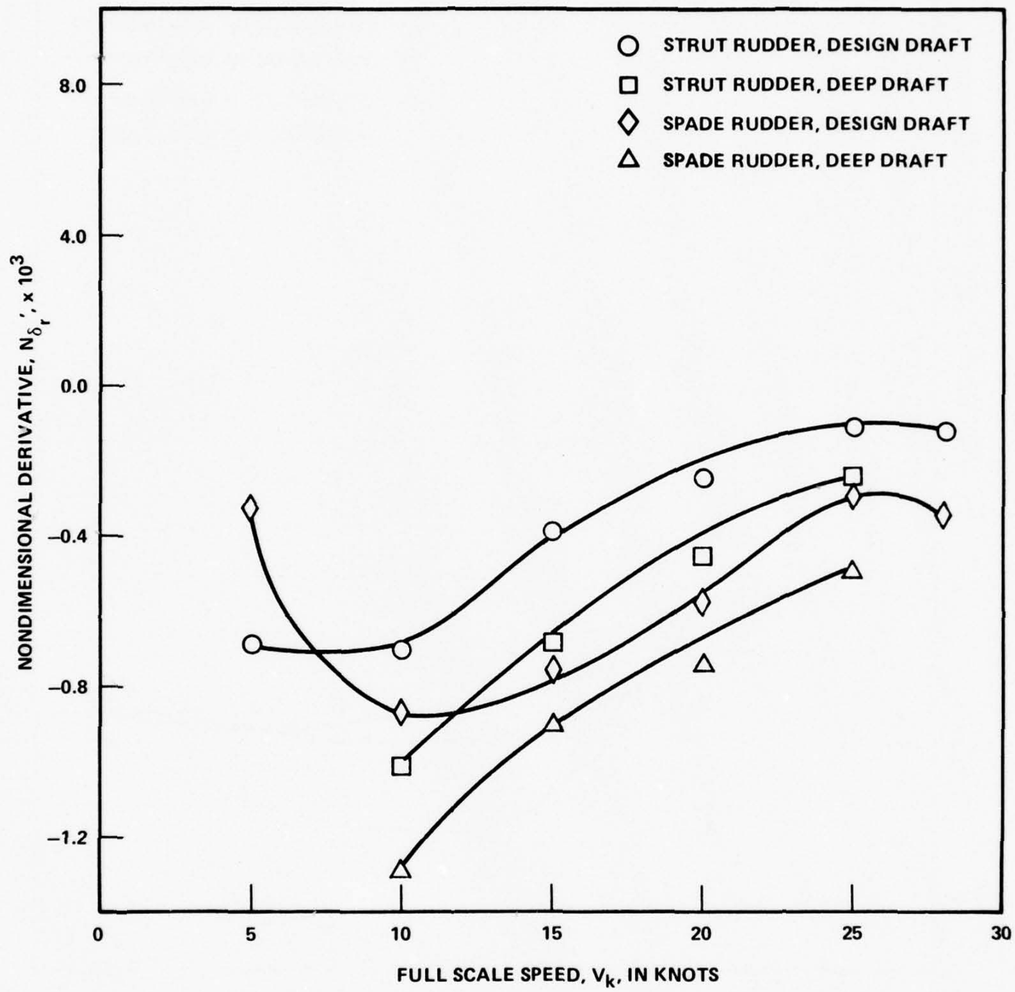

Figure 4 - Variation of Nondimensional Derivative, $N\delta_r'$, for the SWATH 6A, with Full Scale Speed for a Series of Rudder Draft Configurations

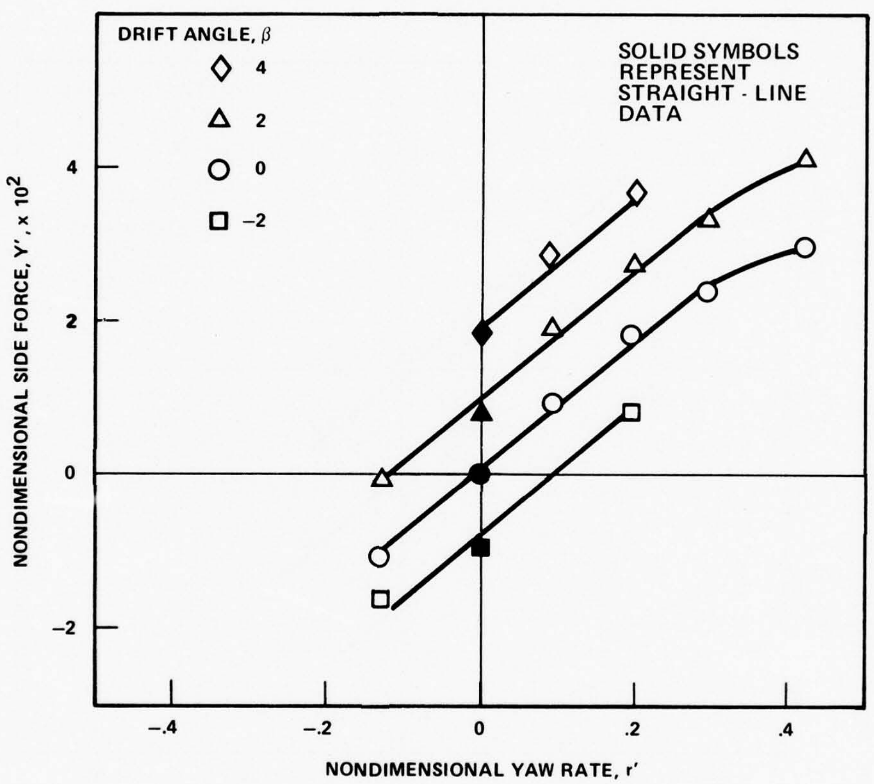

Figure 5 - Variation of Nondimensional Side Force with Nondimensional Yaw Rate for the SSP for a Series of Drift Angles at a Full Scale Speed of 7 Knots at Design Draft

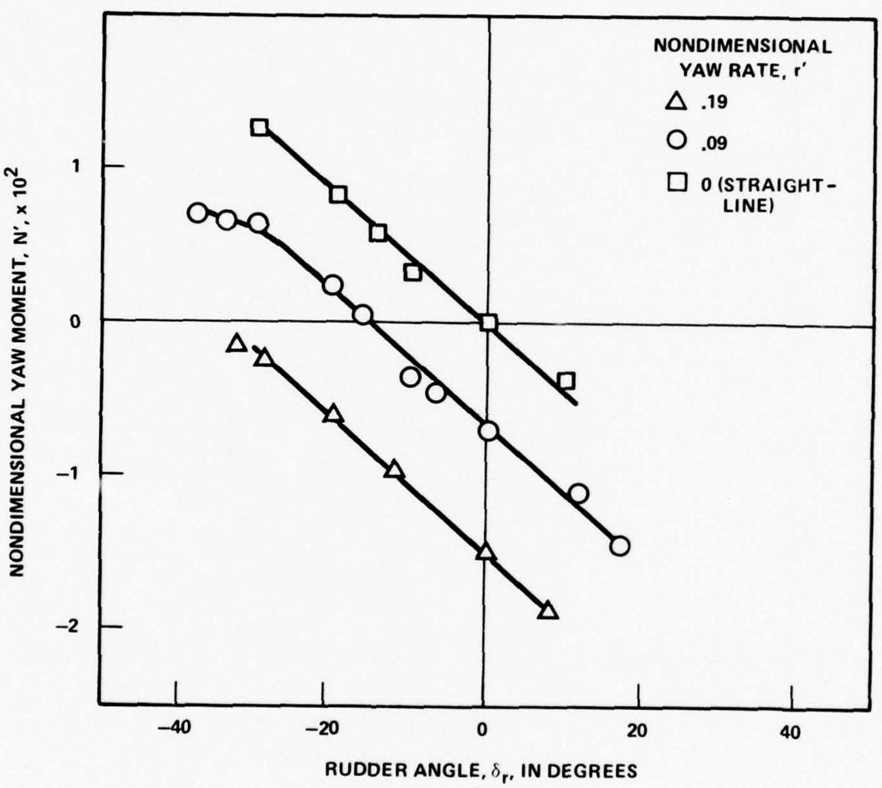

Figure 6 - Variation of Nondimensional Yaw Moment with Rudder Angle for the SSP for a Series of Nondimensional Yaw Rates at a Full Scale Speed of 11 Knots at Design Draft

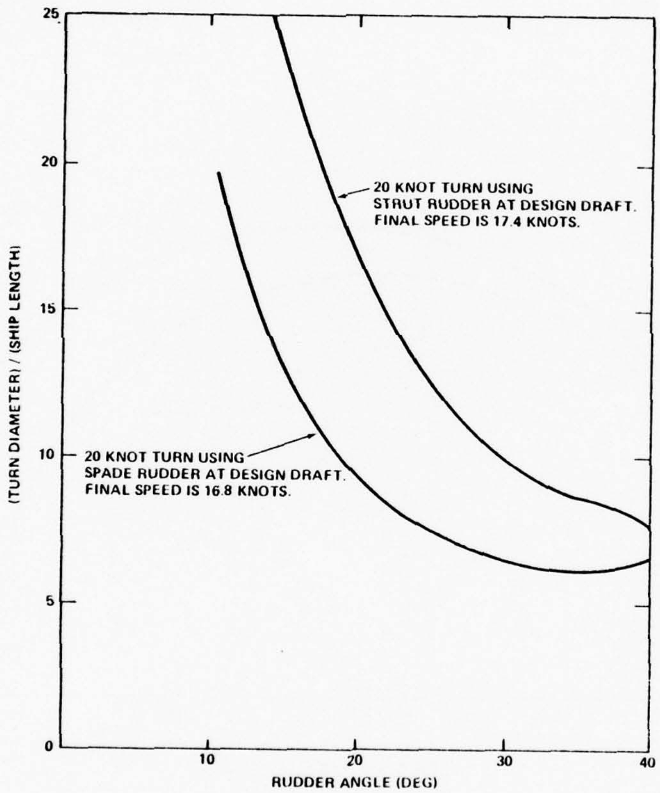

Figure 7 - Comparison of Strut Rudder Turn Diameters with Spade Rudder Turn Diameters at Design Draft for the SWATH 6A Configuration

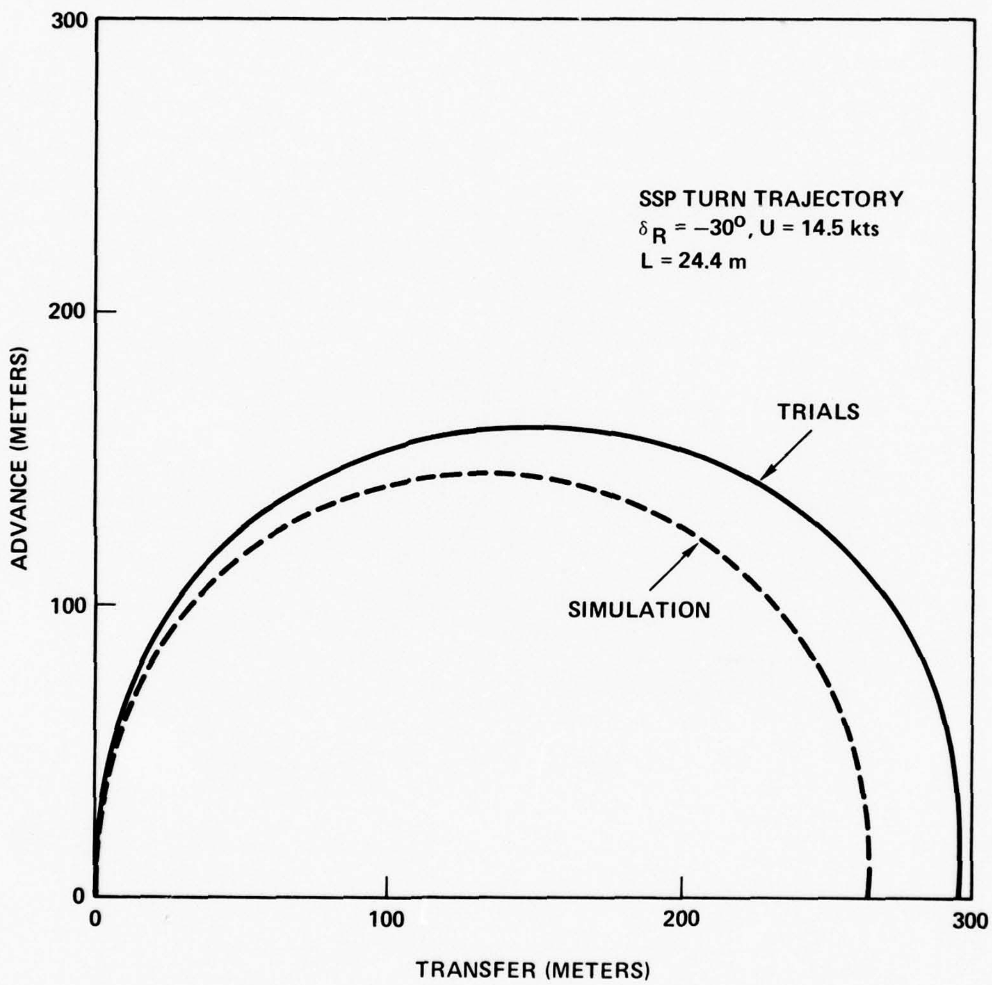

Figure 8 - SSP SWATH Turning Trajectories for the Simulation and Full Scale Trials

Report of the System and Techniques Committee

The Systems and Techniques Committee consisted of Mr. P. W. Brown, Chairman; Mr. W. Barkley; Mr. G. G. Dobay; Dr. D. Gospodnetic; and Professor B. Johnson.

The past three years since the 17th American Towing Tank Conference has been a period of consolidation, during which time the systems and techniques reported to previous conferences have been developed and refined. Progress in some areas has been slower than anticipated including for example the development of laser anemometry.

The developments that have taken place have been specific rather than general, the most notable of these being the completion of the new facilities of the Hydromechanics Laboratory at the U. S. Naval Academy in Annapolis, Maryland. Consequently this Committee considered it would be more informative to invite contributions dealing with these specific developments rather than to offer a series of surveys which would be largely repetitious at this time.

There are six contributed papers, four of which deal with the new systems at the Hydromechanics Laboratory including as topics: Data acquisition, control and analysis system; Optical data transmission system; Computer controlled wave generation system and Dual flap wave maker design. In addition there are reports on: Digital control of D.C. tank drives and Prediction of breaking waves in a towing tank. A movie on Experimental techniques for studying aircraft trailing vortex systems was shown during the conference session and an oral presentation on the new model basin equipment at Webb Institute of Naval Architecture was given.

In the area of instrumentation the Committee noted the need for the development of a non-contacting wave gage. The obvious advantages of such a gage are that the water surface is not disturbed by the gage and at high speed the problems of gage deflection, speed dependent calibrations and flow separation association with surface piercing gages are avoided. The applications for such a gage are not limited to conventional wave height measurement. There is also the need to determine the water elevation in the air cushion under surface effect ships and air cushion vehicles. Current versions of the non-contacting sonic wave probe have a limited application due to the fact that they are sensitive to wave slope as well as wave height, leading to distortion and loss of signal.

AN OPTICAL DATA TRANSMISSION SYSTEM FOR TELEMETRY AND CONTROL APPLICATION

by

B. Grabois
ITT Gilfillan

ABSTRACT

The Optical Data Transmission System for the U.S. Naval Academy Towing Tank facility provides real time, wideband duplex data transmission between the moving carriages and fixed shore locations. Data transmitted comprise both multichannel instrumentation telemetry and high resolution TV video. The data modules are designed to interface with instrumentation typically used in hydrodynamic testing. Modular design permits flexibility with respect to the number and bandwidth of data channels.

Two Argon spectral lines generated by a single laser are used; one for digital, the other for video transmission. The two lines are combined, after modulation, in a single output beam. The power density is at an eye safe level as defined by applicable government regulations. Spectral filters separate the received signals which are processed individually to realize useful data outputs.

The use of optical links eliminates trailing cables and electrical interference problems associated with RF transmission. Although designed for a towing tank, the equipment may be utilized in a variety of instrumentation applications.

Introduction

Optical data link systems have been developed by ITT Gilfillan specifically for application in towing tank test facilities and been supplied to both the modern one-kilometer Naval Ship Research and Development Center (NSRDC) at Carderock, Maryland, and the newly constructed U.S. Naval Academy (USNA) Facility at Annapolis, Maryland. In both applications, the ITT data links provide wideband duplex data transmission between the moving carriages and fixed shore locations. The data transmitted comprise both multichannel instrumentation telemetry and high resolution TV video to and from the carriages. The modular equipment design permits user selection of the number and bandwidth of data channels required for particular needs, and system expansion using standard circuit boards and assemblies. The data modules are designed to interface with the instrumentation typically used in hydrodynamic testing.

The principal advantages of an optical data link, in tow tank and similar applications, include:

- o Real time off-carriage data processing
- o Elimination of RF interference with other instrumentation
- o EMI immunity
- o Freedom from trailing cable limitations
- o High channel capacity and wide bandwidth
- o High reliability

- o Simple installation and ease of maintenance
- o Data flexibility and growth potential.

This paper describes the Optical Data Transmission System (ODTS) supplied by ITT Gilfillan for the USNA towing tank test facility.

Functional Description

The ODTS provides a transparent data link comprising both analog and digital channels on a common optical beam. The self-contained equipment transmits multiplexed telemetry data at sampling rates of 3.35 Mb/sec, 209 kb/sec, and 20.9 kb/sec. The telemetry analog inputs are converted to digital signals with a resolution of 12 bits, for accurate and large dynamic range transmission, and then back to analog outputs in the receiver unit at the levels and impedances of the original input signals. The digital transmission link bit error rates are well below one part in 10^8. In addition to the multiplexed digital data transmission, the ODTS simultaneously provides a 12 MHz baseband analog channel. This wideband video channel permits transmission of high resolution television information with a signal-to-noise ratio of 40 dB for the full bandwidth (110 dB in a 1 Hertz bandwidth). The total harmonic distortion of this channel is less than 5 percent for all harmonic components within the passband, from input to output, inclusive of compensation networks for long line drivers and data filters.

The equipment supplied for the USNA towing tank provides four communication links as depicted in Figure 1; four receivers and three transmitters are used. The output of one of the three transmitters is routed to two receivers – one located on the low-speed, the other on the high-speed carriage – providing control capability to either platform from a single unit.

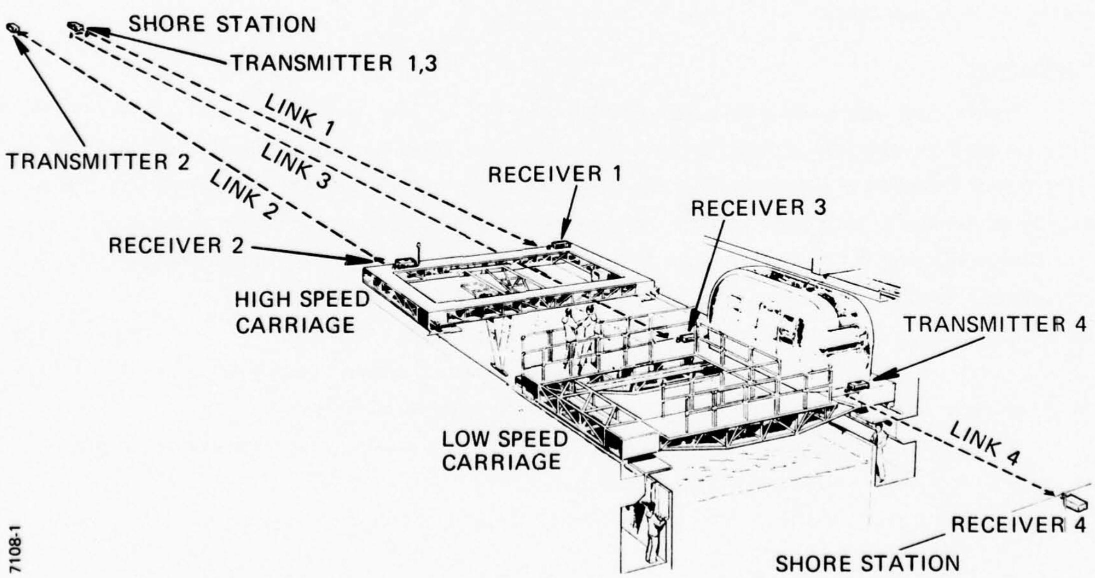

Figure 1. Optical Data Transmission System as Deployed at the U.S. Naval Academy Towing Tank Facility

The hardware elements of the ODTS, their physical size, and power requirements are included in Table I. Except for the optical units, all system components are designed for mounting in standard 19-inch instrument racks. The external reflectors, indicated in Table I, are available should it be necessary to mount a transmitter optical unit in a location where line-of-sight to the receiver is not convenient or achievable. The beam divider is a power-splitting device that allows a single transmitter unit to supply data simultaneously to two receivers. The data channels utilized at the separate receivers are selectable, and the same or different information may be used by each even though supplied by a common transmitter unit.

TABLE I. ODTS PHYSICAL CHARACTERISTICS AND POWER REQUIREMENTS

Unit Name	Quantity		Size (Inches)			Unit Weight (Pounds)	Link Input Power*** (Watts)
	One Link	Supplied USNA	Width	Height	Depth		
Transmitter							
Transmitter Optical Unit (TOU)	1	3	12.5	6.8	30.75	58	1,000
Modulator Driver	2	6	19.0	15.75	24.25*	60	
Laser Power Supply	1	3	19.0	7.3	24.25*	33	
Transmitter Control Panel (TCP)	1	3	19.0	10.5	18.7	33	100
External Beam Splitter	**	1	4.5	5.25	3.5	2	0
External Reflector	**	5	4.5	5.25	3.5	2	0
Receiver							
Receiver Optical Unit (ROU)	1	4	10.0	7.5	18.0	35	50
Receiver Control Panel (RCP)	1	4	19.0	10.5	18.7	35	115

*Shelf Depth
**As Required
***Input at 115V, 60 Hz, 1φ input.

The ODTS normally operates from an external synchronization signal in order to achieve compatibility with the data processing equipment used as an integral part of the facility. An internal reference is also available, selectable from the transmitter control panel, permitting operation without an external timing signal. This feature results in the ability to test and align the ODTS without activating ancillary equipment.

The ODTS can be operated either from the control and connector panel or from a remote location. A single ON/OFF switch operates all elements of the system associated with that particular transmitter or receiver connector panel. The transmitter laser warmup time is fifteen minutes and the receiver unit requires no warmup.

The ODTS is essentially a transparent link providing output signals identical (in level, impedance, etc.) to the inputs. The connectors on the transmitter and receiver panels are arranged and labeled identically so that the user can patch data into and out of the link using any of the available ports without reference to instruction manuals. The receiver panel contains meters that continuously monitor the link signal strength as an indication of the operational status of the system. In addition, a visual indicator displays the readiness of the digital data link.

Digital Data Processing

The digital data link utilizes time division multiplexing (TDM) to take advantage of the high information carrying potential of laser beams and, thereby, provides the communication capability required for the USNA towing tank facility in a single link. The TDM carrier in the digital link is multiplexed in three stages. The first stage operates at a clock rate of 10.06 MHz and develops two data channels, each with a 3.355 Mb/sec capacity, and a third for further multiplexing. The third channel undergoes a second stage of multiplexing creating sixteen medium speed channels, each with a sampling rate of 209 kb/sec. One of these 209 kb/sec channels is further divided to provide ten low-speed channels, each with a sampling rate of 20.9 kb/sec. One of the low-speed channels is dedicated to transmitting a digitized audio signal which is recovered at the output by means of digital-to-analog conversion. The audio is recovered with low distortion at the receiver and provides capability for voice communication between stations.

Plug-in circuit cards for digitizing analog signals were supplied as part of the USNA ODTS. These cards can be added to any link as needed, subject to available channel capacity for special instrumentation requirements. The plug-in circuit cards permit transmission of: 40 kHz baseband, or two separate 20 kHz, signals; and eight 1 kHz bandwidth signal channels. The 40 kHz signals are sampled at the rate of 5.175 samples per cycle of signal and the 1 kHz signals at 8.738 samples. Both the 40 kHz and the 1 kHz channels have a 12 bit resolution resulting in excellent fidelity of the received signals.

The available data transmission capability of the ODTS and channel requirements for the analog data are summarized in Table II. Although the transmission capacity delineated in the table is available to the user, not all are utilized in the ODTS supplied to the USNA.

TABLE II. CHARACTERISTICS OF OPTICAL DATA LINK

VIDEO CHANNEL

Quantity:	1
Bandwidth:	12 MHz
S/N Ratio:	110 dB/Hz
Linearity:	5%

DIGITAL CHANNELS

Function	Quantity	Sampling Rate	Error Rate
High Speed	2	3.35 Mb/sec	< 1 part 10^8
Medium Speed	14	209 kb/sec	< 1 part 10^8
Low Speed	10*	20.9 kb/sec	< 1 part 10^8

*One channel dedicated for voice communications.

ANALOG INPUT CHANNELS

Function	Quantity	Band-width	Quantization Levels	Digital Channels Required
Voice	1	3 kHz	2^{10}	1 - 20.9 kb/sec
Wide Band A or	1	40 kHz	2^{12}	12 - 209 kb/sec
Wide Band B	2	20 kHz	2^{12}	12 - 209 kb/sec
Narrow Band	8	1 kHz	2^{12}	4 - 209 kb/sec

Optical Units

Since both wideband video and high bit rate digital data are transmitted, two transmitters and receivers are required for each link. The Argon ion laser generates several spectral lines, but the major portion of the energy is concentrated in two optical frequencies. This characteristic of the Argon laser was utilized in the ODTS to combine the two communication links – video and digital – in one optically-multiplexed transmitter and receiver. As a result of deriving the two optical carriers from a single source, complexity is decreased, reliability improved, and spare part requirements reduced.

The transmitter and receiver optical unit block diagrams are shown in Figure 2. The transmitter unit consists of the Argon ion laser, two acousto-optical modulators, and various beam folding mirrors and dichroic filters.

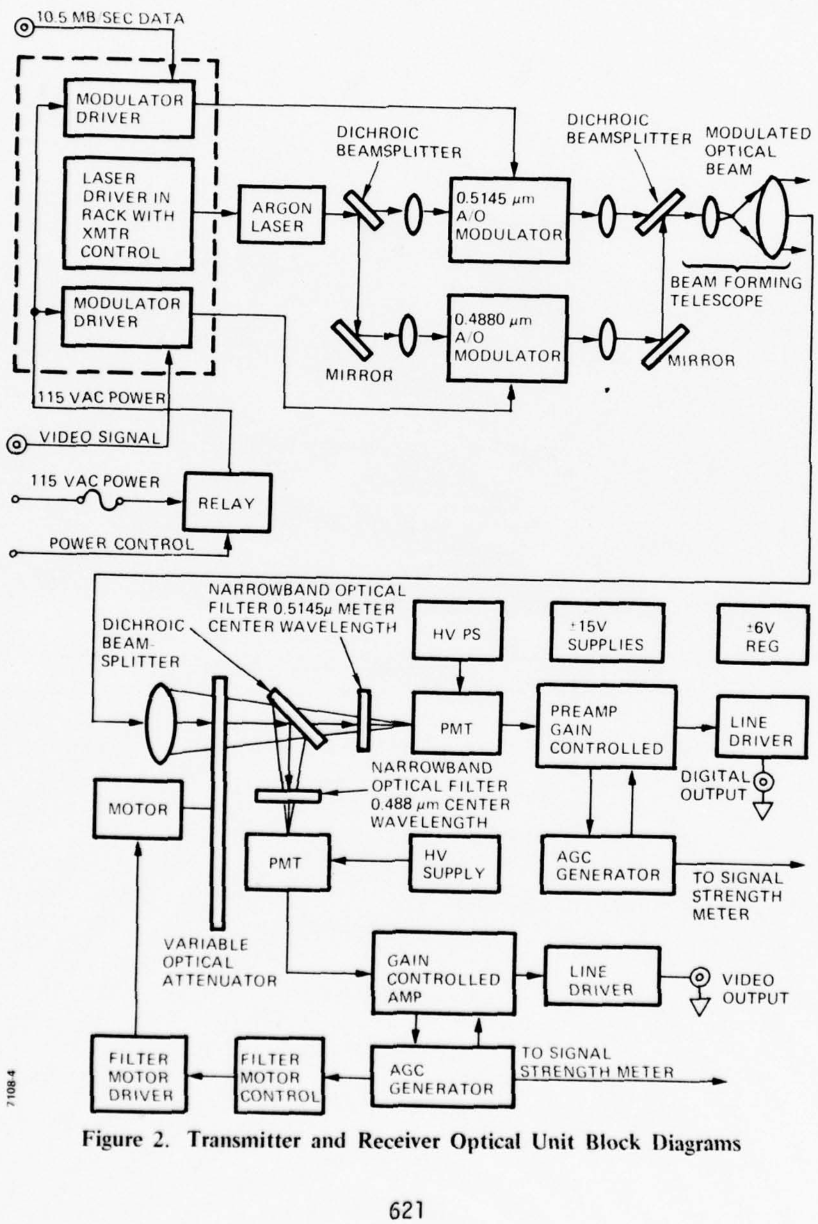

Figure 2. Transmitter and Receiver Optical Unit Block Diagrams

The Argon laser provides cw output power at both 0.488μ (blue) and 0.5145μ (green) simultaneously. The output of the ODTS laser is adjustable at the laser power supply front panel; maximum optical powers of 10 milliwatts at 0.488μ and 5 milliwatts at 0.5145μ are available. The laser output beam is spectrally divided by a dichroic beam splitter; the 0.488μ beam is modulated by the video channel modulator and the 0.5145μ by the digital modulator. After modulation, the two beams are recombined and directed through the beam forming output lens. The output beam divergence is set with a focusing adjustment beam expander lens to be approximately 0.1 degree. This beam divergence is sufficiently broad to permit easy alignment and is well within the carriage angular stability tolerance. Figure 3 shows the optical components in the transmitter unit.

The system is completely eye safe and in compliance with the requirements of the Department of the Army Technical Bulletin TB MED 279 on safe use of laser radiation.

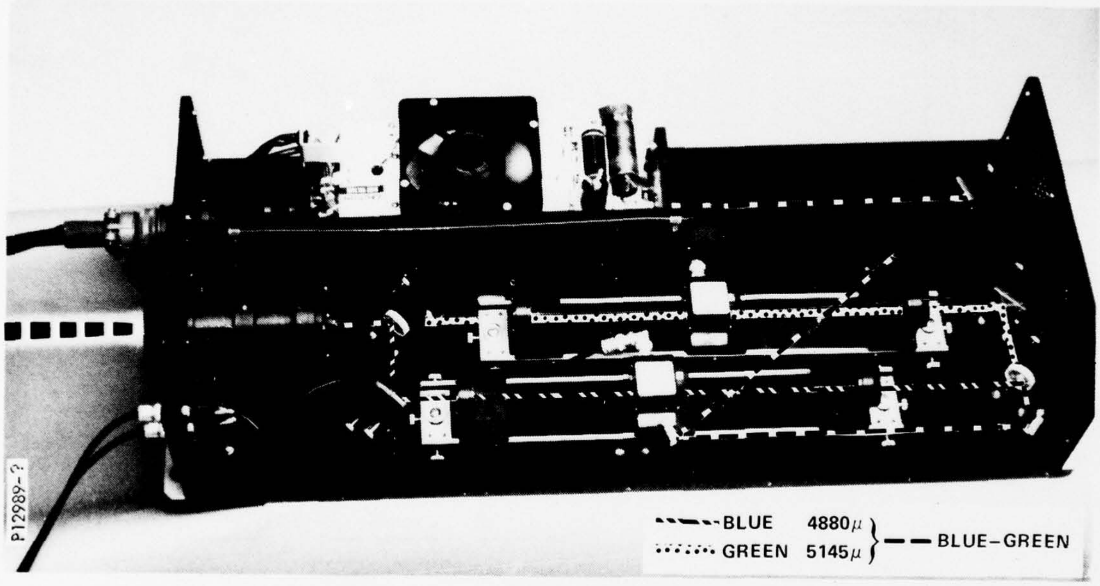

Figure 3. Optical Transmitter With Cover Removed to Show Major Components

The modulator employed is of the acousto-optical type and provides intensity modulation by diffracting the input beam into two output beams in proportion to the amplitude of the driving signal. An acoustic wave in the modulator is generated in a lead molybdate plate by a piezoelectric transducer driven by the modulating signal. This acoustic wave produces a change in the density and dielectric constant of the lead molybdate medium at the spatial frequency of the acoustic wavelength (λ_a) in the medium; the resulting effect is similar to a diffraction grating on the optical beam. When no modulation is applied the total input optical beam power exits in the "zero" order direction; with modulation applied, a portion of the input power is diffracted into the "first" order direction at the output as illustrated in Figure 4. The acoustic wave is provided by an RF oscillator whose output is amplitude modulated by either the digital information signals or a 16 MHz subcarrier on which the video signal is impressed. The frequency of the RF carrier determines the angular separation of the zero and first order diffracted beams, and the amplitude of the RF carrier determines the modulation depth. Both outputs are usable; the ODTS uses the first order signal and the zero order is masked. The relation ship between the diffracted light output, I_1, and the amplitude of the applied signal, V, is:

$$I_1 \propto \sin^2 KV$$

where K is a constant.

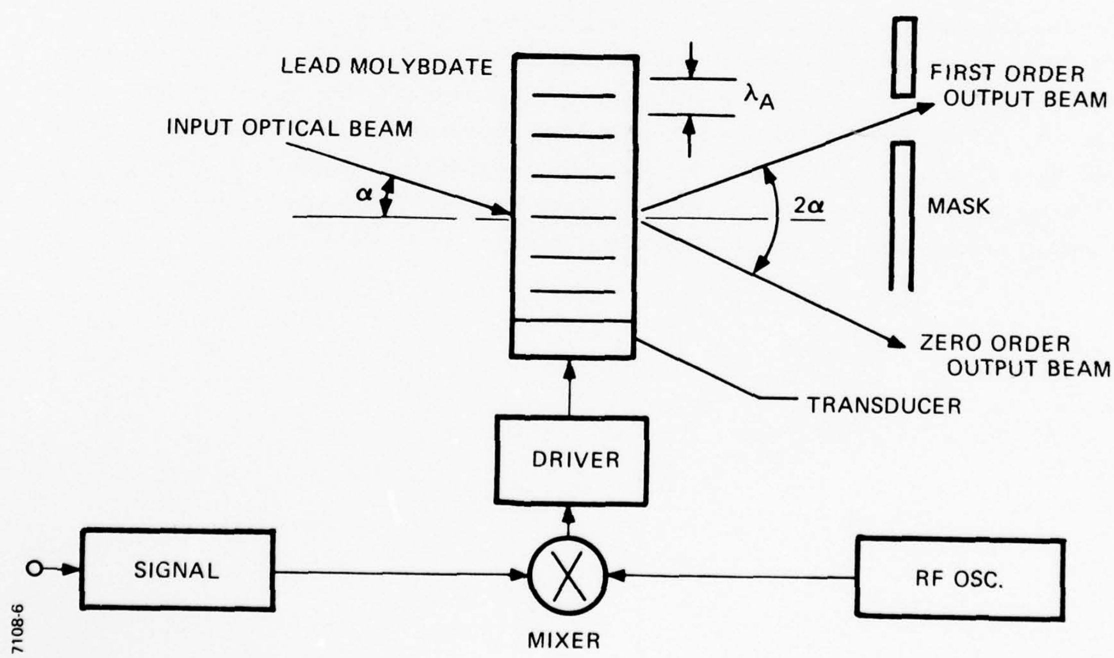

Figure 4. Schematic Representation of Acousto-Optical Modulator

The receiving lens collects a portion of the transmitted power and after separation by a dichroic beam splitter focuses it onto two photomultiplier detectors. The beam splitter spectrally divides the received power into the 0.488μ (analog) and 0.5145μ (digital) components. The photomultiplier detectors are identical, but the output preamplifiers are designed for the particular signals – either analog or digital. Narrow-band optical filters are inserted in the optical paths just ahead of the detectors to provide both background radiation suppression and channel cross-talk reduction. The receiver contains a motor-driven variable optical attenuator controlled by the video channel AGC amplifier. This optical filter maintains the received signal power below the maximum safe current level at the detector output. The filter is a coarse control, and individual AGC amplifiers in the digital and video preamplifiers provide fine control. The video AGC preamplifier is capable of accommodating a 50 dB dynamic range.

The video and digital signals are processed, demultiplexed, conditioned, and distributed in the Receiver Control Panel; the front panel connector nomenclature corresponds to that on the Transmitter Control Panel which facilitates use of the equipment.

Summary

The ODTS provides both video and digital data transmission capability utilizing a single laser beam. The video channel provides a 12 MHz bandwidth with a 40 dB signal-to-noise ration permitting transmission of high resolution television information. Twenty-five digital channels are available including high, medium and low sampling rates. A channel for voice communication is a convenient feature for operational personnel. Plug-in circuit cards which digitize analog signals for transmission on the digital channels are available to extend the capability of the system.

Corresponding system elements are physically and functionally interchangeable, thus providing flexibility and adaptability for different applications, fewer maintenance procedures, and reduced spares provisioning. Because of the small optical beam diameters and low divergences, the optical beams can be easily manipulated by means of the small ancillary optical components to facilitate equipment location and alignment. This alignment approach provides considerable latitude in location and orientation of the optical units. Since the optical beams are visible, they can readily be adjusted without auxiliary test equipment.

The large number of data channels and the modular design of the ODTS result in its being applicable to a variety of applications that require transmission of data to remote sites in real time.

The U.S. Naval Academy

Hydromechanics Laboratory Data Acquisition,

Control, and Analysis System

The capabilities of the data acquisition, control, and analysis system for the new Hydromechanics Laboratory at the U.S. Naval Academy in Annapolis, Maryland are described.

The integrated facility, consisting of 120 ft and 380 ft towing tanks, an ocean engineering tank, and a circulating water channel, is designed to easily accept a variety of tests with a minimum of setup time between tests.

All of the test facilities utilize an advanced, integrated, time-shared data acquisition, analysis, and control system which optimizes the educational value of experimental hydromechanics by minimizing nonproductive manual setup, data recording, and routine calculations. Results are immediately available to the students to reinforce and give meaning to their visual observations.

Authors:

Dr. John C. Gebhardt
Mr. Seymour Williams, III
Dr. Roger H. Compton

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I INTRODUCTION

The Hydromechanics Laboratory Complex is a loosely integrated group of experimental facilities within the Rickover Hall Engineering studies complex. It consists of

- o a 380 ft towing tank with high-speed and low-speed carriages, a computer-controlled dual-flap wavemaker, and excellent surface/underwater observation capability
- o a 120 ft towing tank, also with a computer-controlled dual-flap wavemaker and geometrically similar cross-section to the large tank ,
- o a 40 ft x 48 ft ocean engineering tank with shallow-water wavemaking capability , and
- o a circulating water channel with a 16 in. x 16 in x 5 ft free-surface test section .

All facilities are designed either to be operated manually or controlled to various degrees by a large minicomputer-based multi-user data acquisition, control, and analysis system. The system can at least acquire, store, analyze and display analog data generated at each facility. In addition, the computer system can control the operation of three wavemakers, the two carriages in the 380 ft tank and the carriage in the 120 ft tank, making it possible to execute standard towing tank tests in a completely automated mode.

In this paper, we attempt to describe the data acquisition, control, and analysis system, primarily from a software viewpoint.

The discussion will, hopefully, point out the importance and desirability of designing and implementing systems using a top-down approach. It is becoming increasingly apparent that the rigid discipline imposed on the software development effort, with regard to documentation, review cycles and coding procedures, is largely responsible for the initial success of the system.

II THE COMPUTER SYSTEM

II-1 General

The computer system is located in the 380 tank control room and serves the data acquisition, control and analysis needs of the 120 ft tank, the 380 ft tank, the circulating water channel, and the ocean engineering tank. It consists of a central processor, two disk units, two magnetic tape units, a printer/plotter, an array processor, a digital television display system, a high-density digital tape recorder, a wavemaker controller and sea-state processor, and interfaces to terminals, carriage controllers, and data acquisition systems. A simplified block diagram of the hardware is shown in Figure II-1.

II-2 Central Processor

A Digital Equipment Corporation (DEC) PDP-11/50 minicomputer serves as the system control element. This is a state-of-the art, general-purpose 16-bit minicomputer. Some of its capabilities and features are

a) central processor has 300 nanosecond cycle times; sixteen general purpose registers, floating point arithmetic, power fail/restart; four-line, multi-level hardware interrupt system with seven levels of software interrupt priority; able to address both 16-bit words and 8-bit bytes,

b) capability of addressing 128K words of memory,

c) line frequency clock providing interrupts every 16.6 msec,

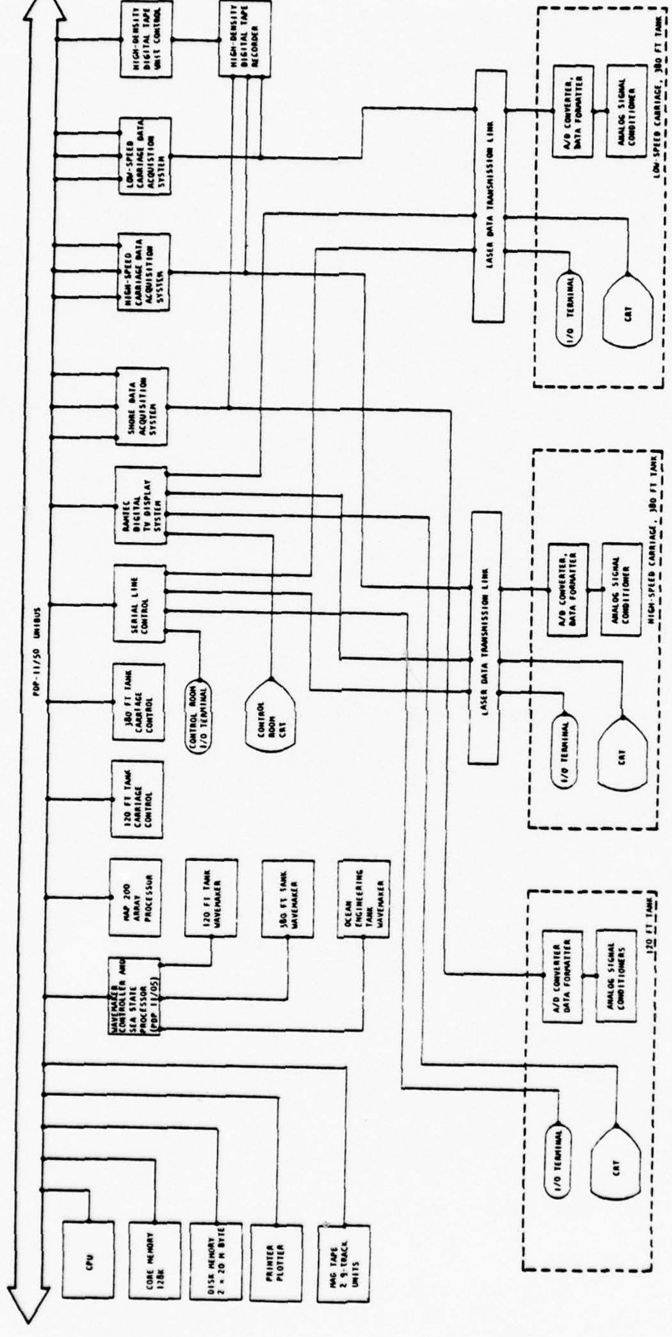

FIGURE II-1 COMPUTER SYSTEM BLOCK DIAGRAM

d) hardware floating point processor which performs arithmetic operations on 32-bit and 64-bit floating point numbers and performs integer-to-floating conversions ,

e) hardware memory management,

f) two input/output busses (One bus reserved for addressing 450 nanosecond MOS semiconductor memory. The other bus for general purpose transfers between core and the processor and to peripheral devices. The general purpose bus supports direct memory access DMA without processor intervention.), and

g) software is available to support assembly language and FORTRAN IV.

<u>II-3 Memory</u>

Main storage is provided by 128K words (16-bit) memory. This consists of 32K words (16-bit) of MOS memory with a cycle time of 450 nanoseconds, and 96K words (16-bit) of 900 nanosecond core memory.

II-4 Mass Storage

Mass storage is provided by two DEC RP03 moving head disk drives and associated controller. This drive has a removable disk pack with 19 recording surfaces per pack, provides on line storage for 20,480,000 words (16-bit) and is supported by the RSX-11D real time operating system.

Two DEC TU10 industry compatible, nine-track tape transports and a controller/interface to the PDP-11/50 are provided for archival storage of data, software, and as disk backup. These drives are supported by the RSX-11D real time operating system.

II-5 Electrostatic Printer/Plotter

A VERSATEC matrix 1100A printer/plotter and its associated controller/interface provides both printed and graphic output.

II-6 Raster-Type Graphic Display System

A RAMTEK GX-100B graphic display system displays computer generated data in graphic form. This system has hardware refresh. Four monochromatic 14" diagonal display screens are located as shown in Figure II-1. The system allows an average access time to any element on the screen of 8 msec and a maximum access time of 16 msec. A complete page can be written in 16 msec. This unit features 512 line by 512 element resolution, and generates 5 x 7 dot matrix alphanumeric characters.

II-7 Input/Output Keyboard Devices

Four DEC LA36 DECWriter units provide for hardcopy input/output and control.

II-8 Hardware Fast-Fourier Transform Processor

A CSPI Map 200 Array processor provides high-speed time series analysis capabilities.

II-9 Wavemaker Control and Seastate Processor

A PDP-11/05 processor with 24K 16-bit words of core memory is used to control the wavemakers. Wavemaker calibration and control software is stored on a 1.2 M word cartridge disk, while waveform time histories are stored on a tape cassette system. This system is discussed more thoroughly in Anderson and Johnson, " A Computer Controlled Wave Generation System for the United States Naval Academy ", Reference 1.

II-10 High Density Digital Tape Recorder

A Sangamo Sabre IV tape recorder is controlled by a Systron Donnor time code reader and tape search unit, which is interfaced to the central processor. The HDDR is used to record PCM data directly from the data link at very high data rates and to play back the recorded data at speeds more acceptable for computer processing.

III SOFTWARE PHILOSOPHY

III-1 Background

During the initial design of the facility, it became apparent that in order to take full advantage of the tremendous potential of the facility with the limited staff available at the Naval Academy, it would be necessary to partially automate the acquisition and analysis of data. After deciding that a dedicated minicomputer was needed for the acquisition and analysis tasks, it was a simple matter to interface the computer to the digital speed control systems and let the computer actually control the carriage operation.

The concept gradually evolved to the prototype stage with the AUTOTANK system (see Reference 2), an interactive real time, data acquisition and analysis system written by CADCOM, Inc. and implemented on the Naval Academy's PDP-15/40 computer, which was located near the old 85 ft towing tank. AUTOTANK, although it could not actually control the carriage, demonstrated the feasibility of the concept of a flexible, high-level language for automating the operation of a towing tank.

III-2 Requirements

Based on the lessons learned from AUTOTANK, the requirements for the current system evolved:

- The software system must operate within the environment of a proven, capable multi-user, multi-task, real-time operating system.

- The system must be structured as a high-level language with which the test engineer can perform a wide variety of tests .
- The system must allow tests to be written in the high-level language and stored on files to be executed later as "automated" tests.
- The system must accept numerical inputs in arbitrary user-specified units, but perform all internal calculations in some fixed set of units.
- The system must support simultaneous operation of high and low speed carriages and the 120 ft tank.
- A central data base must be provided for storing acquired data and computed results in easily accessible formats.
- The system must be comfortable for test engineers, naval architects, and students to use.
- It must provide tabular and graphical output for standard towing tank tests suitable for publication in test reports.

III-3 Implementation

Computer Sciences Corporation, immediately upon award of their contract, began development of the software system using a highly structured system based on extensive documentation and frequent meetings with the ultimate users of the system. The documentation system is based on four types of documents, the Baseline Definition, the Requirements Documents, the System Design Documents, and the Final Documentation.

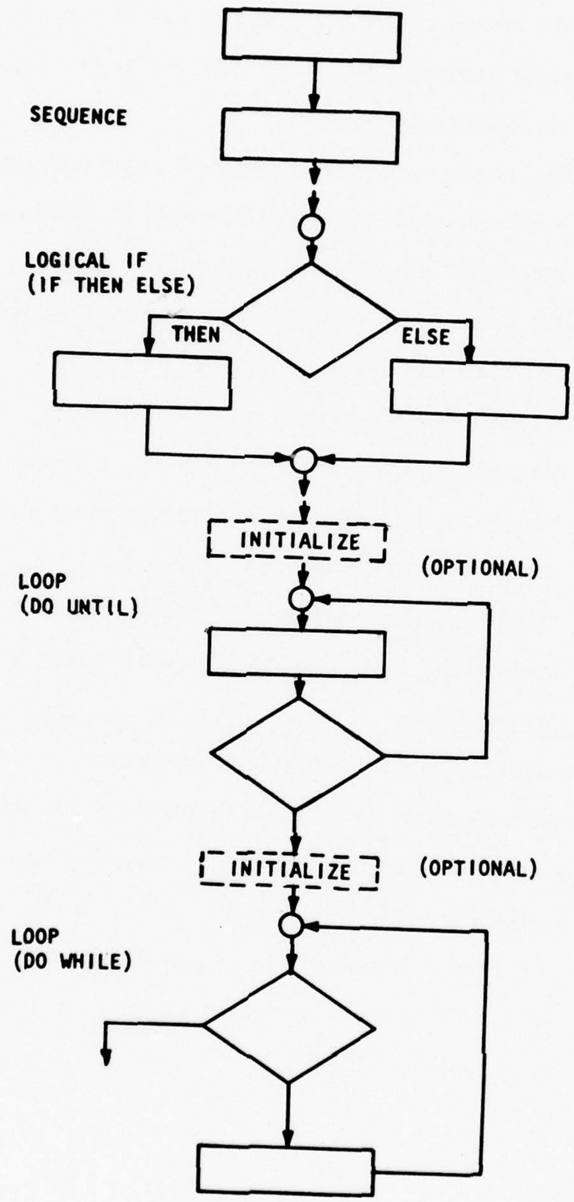

FIGURE III-1 BASIC LOGIC STRUCTURES FOR STRUCTURED PROGRAMS

The Baseline Document is CSC's interpretation of the software specifications issued as part of the contract. It was developed after many long meetings with the Navy, CADCOM, and CSC, and represented the consensus of everyone involved.

It described, in as much detail as possible, the system software, test structure, test setup, test execution, data analysis, calibration, computational utilities, and test outputs. Also included were desired features considered to be outside the scope of the project.

The Baseline Document was then expanded into a series of documents, the Requirements Documents, which described in more detail the major software modules of the system. As this preliminary design for each module was completed, it was reviewed by the Naval Academy and a meeting was usually held to discuss the function, structure, or user interface.

The Requirements Documents describe the function of each module, the inputs required by the module, the outputs produced by the program, and general block and flow diagrams. Once each Requirements Document was formally reviewed and accepted by the Naval Academy, the system design for the module was initiated, using the approved Requirements Documents as a foundation. Existing sections of the Requirements Document were expanded, and detailed flow charts, operating directions, error stops/exits, and definitions were added. The resulting System Design documents were also carefully reviewed and comments and suggestions were fed back to CSC.

The Final Documentation will consist of essentially updated and revised versions of the System Design documents. A User's Guide is being assembled using only those selected sections of the System Design documents, which are necessary for normal operation of the system.

All of the modules, subroutines, and programs within the system are designed and coded using "structured programming" techniques which are based on the premise that the only "proper" program is one that has one and only one entry and one and only one exit. It can be shown that a "proper" program can consist of only the following logic structures (See Figure III-1):

a) sequences of two or more operations;

b) conditional branches to one of two operations and return to a common point, and

c) looping, with no exits from the loop other than the terminal point.

As an adjunct to these basic principles, two rules are also followed:

a) The program is organized on the printed page to highlight logical relationships. For example, loops are indented.

b) The program is segmented into reasonable amounts of logic (normally one segment per page), which represents a basic logic structure.

The system that results from the application of these techniques is extremely complex, yet relatively easy to comprehend, maintain, and debug. Most importantly, however, it will do what everyone thought is would do when it was designed.

IV OVERVIEW OF SYSTEM ORGANIZATION AND OPERATION

The software system operates within the context of the RSX-11D operating system; hence, more than one user may be active at one time. The only constraint on multiple, simultaneous testing is that only one of the data acquisition systems may be running at any one time. This restriction may result in short delays (up to possibly minutes in the case of a long low-speed run in the 380 ft tank); but, in most cases, the operator of one tank should be unaware of operations in another tank.

In order to make the system as flexible and modular as possible, the design is based on the operating system's file handling capabilities. All logic modules are stored in task files, all data in data based files. The basic design centers around the concept of a "test". In order for the operator to gain control of the functions described herein, he must activate a "test". A test consists of a series of "runs" where each run represents data at some desired value of a particular test parameter (velocity, wave height, etc.). In some cases, a "subtest" may be defined as a series of runs at the same velocity. When he is through, he must terminate the test. A test activation defines a certain uniqueness to the actions that follow. A unique test number is assigned to the test. A unique run time file is created for the test. This file will contain all pertinent information about the test while the test is active. After the test is over, a unique historical file is created to retain required test particulars needed in the future.

The operator controls the sequence of a test in either the operator interactive (O/I) mode or the automatic (AUTO) mode. In the O/I mode, all commands are executed as they are typed on the DECwriter keyboard. In the AUTO mode, the system asks for the name of the permanent file containing the commands to be executed. The test supervisor will now take commands from that file, rather than from the DECwriter.

The command language offers the operator a collection of test setup, predefined test analysis supervisors, basic test analysis utilities and quick look output capability. In addition, there are limited file control and computational capabilities.

Once a test is terminated, all files associated with the test, with the exception of the historical file, are deleted. This is done to guard against the disk filling up with unimportant files. Commands are available, however, which enable the operator to create permanent files for various test results in order to prevent their destruction.

In the following sections, the basic design concept of each major module is discussed. The tasks in this system are shown in a hierarchical fashion in Figure IV-1. The hierarchy shown is determined by I/O requirements of each module. The less dependent a module is on I/O from other modules, the higher it is in the hierarchy.

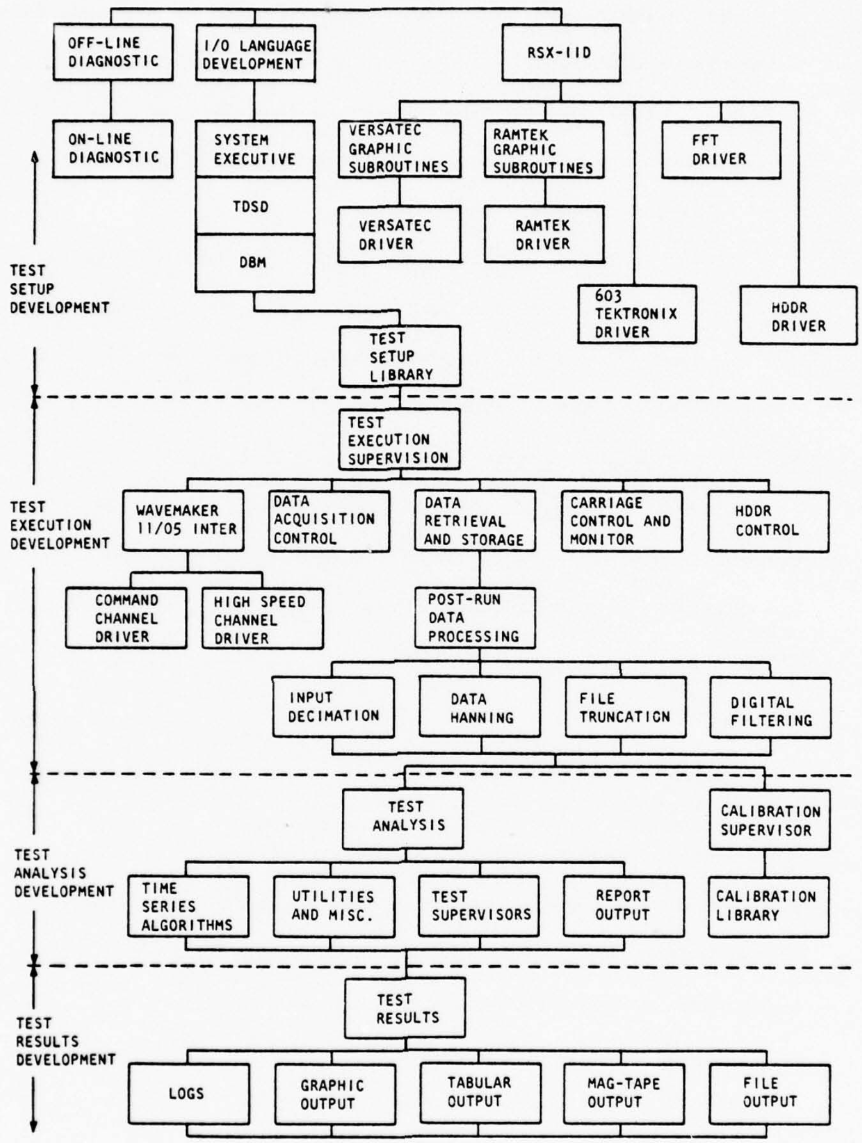

FIGURE IV-1 SYSTEM TOP-DOWN HIERARCHY

IV-1 System Software

The following systems programs and subroutines are considered to be system software:

- the real time operating system, RSX-11D,
- various handlers/device drivers for all of the peripheral equipment and
- a library of graphics subroutines for axes generation, scaling, vector and data plotting, and alphanumeric notation. (These routines will generate both hard copy (Versatek) and CRT (RAMTEK) displays.)

IV-2 Operator Interactive (O/I) Language

The O/I language is the vehicle the test operator employs to communicate with the software system while performing a test. The commands in this language can be grouped into the following categories:

- Test setup
- Test execution
- Test analysis
- Test results (quick look/report quality)

This categorization does not preclude the use of one or more of the commands in a phase of the test not specific to its category. For example, a test setup command can be used in any phase of the test, not just during the setup phase.

The language is used in both the automatic and operator interactive modes of testing, therefore, making it a common language for

the system. With the exception of several commands that are specific to the automatic mode of testing (i.e., MAN,AUTO) all commands can be used interchangeably in either mode.

The language consists of commands, in the general form:

command parameter list

that will convey to the system descriptive information (noun: adjectives) or desired actions (verb:adverbs). The overall goal in designing the language is to make the language usable and keep the language as a tool for the operator to use rather than the operator becoming a tool for the language to use. All commands (nouns and verbs) are a maximum of four alphanumeric characters in length and should be a meaningful abbreviation for the actual command being specified.

The parameter list (adjectives, adverbs) is, of necessity, tailored to the needs of each command. Certain common design features, however, are followed throughout.

- <u>PUNCTUATION</u>

  Parameters are separated by a comma (,). If several parameters go together to form a group, and groups can be repeated in a particular command, the repeating groups are separated by a slash (/). For example,

  command param1, param2, param3

  is a command that does not allow more than one group of parameters.

  command param1, param2, param3 (/param2, param3)

  is a command that has a need for two groups and can optionally accept repeats of the second group.

  A blank always separates the command from the

parameter list. A command line is always terminated by a carriage return (↵)

o <u>BLANK SUPPRESSION</u>

Blanks that are located prior to the first non-blank character or after the last non-blank character in a field are ignored. Imbedded blanks in a field are interpreted as part of the field. For example,

command $\not{b}_1\not{b}_2 10\not{b}_3 0\not{b}_4\not{b}_5$

$\not{b}_1, \not{b}_2, \not{b}_4, \not{b}_5$ are ignored while $\not{b}_3$ is not ignored and will cause a syntax error to be output to the operator.

o <u>LINE EDITING</u>

Line error editing is done by the RSX-11D teletype handler (TT16) and, therefore, is identically the same as all other line editing effort.

o <u>OPERATOR PROMPT</u>

If any field (a field is the area between two commas or a comma and a slash, etc.) is all blank, the command processor will prompt the operator for data with a short (up to 24 characters) English question. Processing on the command will stop until the required data is received from the operator. It should be noted that if the command is given with no parameter list at all, then the operator will be prompted for all parameters. An example of this prompting action is in general:

```
command   param1,  , param3
!command heading
!param2 prompt: (operator response)
```

The prompting is operational in both the operator interactive and automatic modes of operation. Thus, it will not only aid the operator who is not interested in memorizing all the commands and their parameters, but it will allow specification of the command involved in automatic tests without forcing all parameters to be known ahead of time.

In the case where a parameter is optional, its default is employed until after the prompt is ignored. Thus, the operator is prompted on all blank fields and defaults are employed, where applicable, if the default is not answered (done by entering a ↵ with no other characters).

o <u>INPUT ERROR RESPONSE</u>

If the input parameter for any field(s) is found to be in error, the following error message is output:

```
INPUT ERROR - FIELD n - erroneous parameter
```

followed by the prompt message for that field. The field number -n- helps the operator locate the field in error and the erroneous parameter is output for his review to aid in correcting the error. For example, if the operator typed in the following command:

```
CHAN   H1,DRAG,FB01,B2,HEAV,HP02
The computer would respond:
INPUT ERROR - FIELD 4 - B2
CHANNEL    operator response
```

If more fields are input than the command is designed to receive, the following error message is output:

```
INPUT ERROR - TOO MANY PARAMETERS - RE-ENTER
  COMMAND
```

and the operator must re-enter the entire command.

o <u>COMMAND LOGGING</u>

If the operator specifies command logging in the sign-on dialog, each command will be logged by outputting the command header followed by each field prompt and the entered value. For example:

```
The operator enters:
command  param1, param2
```

and the system responds:

```
command header
parameter 1 prompt: param1
parameter 2 prompt: param2
```

This feature gives the operator an English description of the entire test dialog.

o <u>DEFAULT SPECIFICATION</u>

If the operator wishes the system to use the default value for a specific field in the parameter list, he enters an asterisk (*) in that field. The system will not prompt

him for that field, but uses the default immediately. Use of the "*" for fields that do not have default capability is treated as a normal input error.

- CONTINUATION LINES

  No continuation line capability, as such, is allowed in the language format. A command may be repeatedly used, however. If the information contained in the noun is serial in nature, such as that in the CHAN command, repeated use of a noun adds to the information already in the RTF. If the information is singular in nature, such as that in the TANK command, repeated use of a noun overstores the previous information stored in the RTF. Repeated use of a verb causes the action specified to be repeated.

IV-3 System Executive

The System Executive (SYSEX) supervises the execution of the various commands that make up a specific test. As such, the system executive is a general purpose supervisor that will not get involved in the execution of a specific command, but will supply functions common to all commands. Figure IV-2 shows the functional layout of the system executive and the logic modules supervised by it. The system executive accepts command inputs, interprets them, calls the appropriate command processor and passes control to it. The command processors process the command inputs, perform specific functions, and pass results back through the Run Time File for use by subsequent command processing. The Run Time File is a central file that contains information pertaining to a specific test. All test setup information, calibration information, and names of all files created due to test execution, analysis, or output are maintained in this file. This file offers a central file for all processors involved in a test.

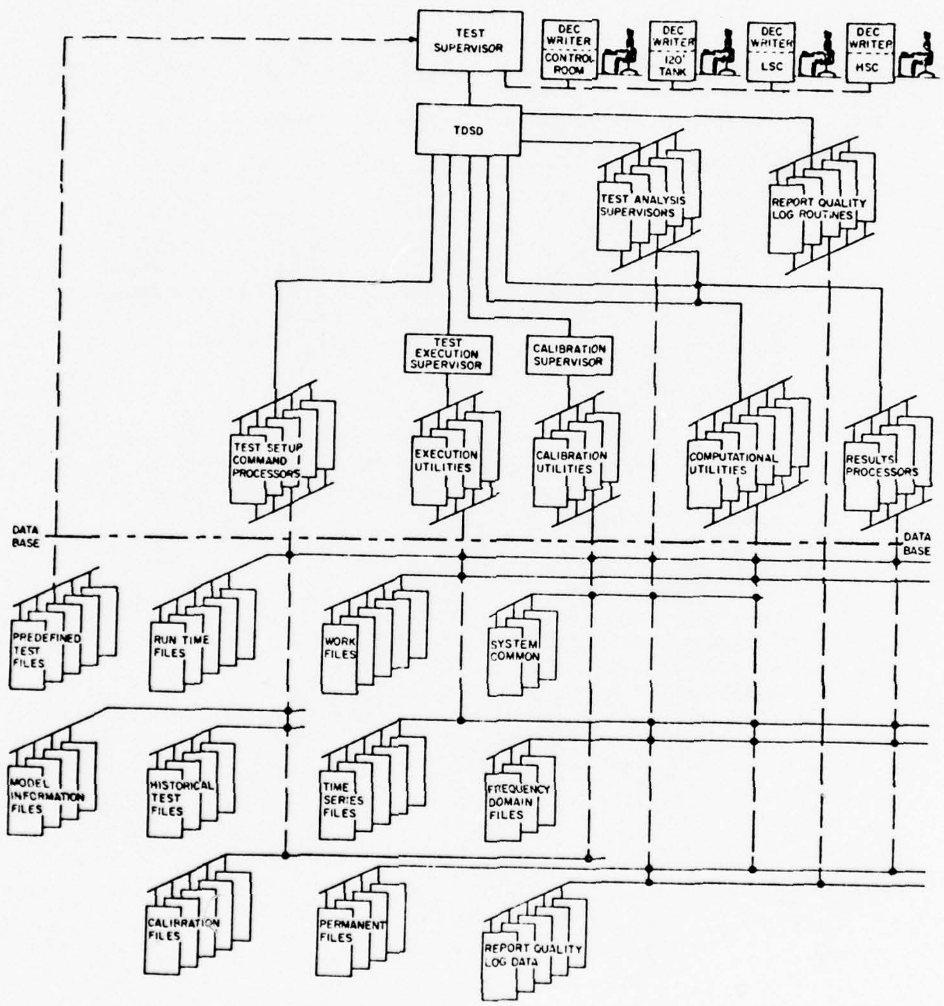

FIGURE IV-2 FUNCTIONAL LAYOUT OF PROCESSORS AND DATA BASE

At the end of each run, the data for the run is analyzed and stored in various files as defined by the specific processing required. Prior to the next run, the time series data files are deleted to make room for the next run.

At the completion of a test, the pertinent information is extracted from the Run Time File for the test and stored in the Historical file. Then all Files associated with this test, including the Run Time File, are deleted from the system.

The system executive provides the following features:

o <u>INPUT SOURCES</u>

Commands will be accepted from the DECwriter (O/I mode) or a named disk file (AUTO mode). Other than the fact that the AUTO mode commands are prestored, there is little difference between AUTO and O/I mode tests.

o <u>COMMAND DECODING</u>

The system executive will decode all commands and perform initial syntax error checking. If syntax errors are found, a diagnostic error message will be output and the entire command will be ignored.

o <u>COMMAND PROCESSOR ACTIVATION</u>

Once the command decoding is complete, the system executive will activate the requested command processor and pass it to the parameter list for processing. The processor will complete the syntax error checks, perform its specific function and upon completion of processing, return to the system executive for processing of further commands.

IV-4 Test Setup

The test setup library is a collection of command processors that provide the user with the functions required to set up or specify a test. The functions of these command processors is to accept descriptive information about the test to be run and to store this information in the Run Time File (RTF). This information will then be used in the later steps of the test (execution, analysis, and results) as necessary. The following is a list of the necessary test setup functions identified to date. Refer to Appendix B for a description of the actual commands.

- o Test Initialization
- o Wave Definition
- o Tank Identification
- o Channel Assignments
- o Revise Channel Assignments
- o Test Sequence Definition
- o Revise Test Sequence
- o Wait Time Definition
- o Calibrate Sequence
- o Transducer Identification
- o Gang Transducer Identification

- Scan Sequence Description
- Frame Data Specification
- Test Data Input Definition
- Select Word Pattern Definition
- HDDR Input Configuration
- HDDR Output Configuration
- HDDR Record Configuration
- DAC Configuration
- Define Temperature Channel
- Model Definition
- Model Identification

One of the major functions which must be performed during the test setup phase is transducer calibration. Figure IV-3 illustrates the dialog necessary to calibrate a transducer; in this case, a force block. The command CDAT can be used for keyboard input if it is not practical to deadload a transducer and acquire the necessary deadload data via the analog to digital converter. Figure IV-4 is an example of a calibration plot generated by the DISP verb.

IV-5 Test Execution

Once the test setup sequence has been completed, sufficient information exists in the Run Time File to supervise the execution of each of the test runs specified. This supervision is broken down into three areas:

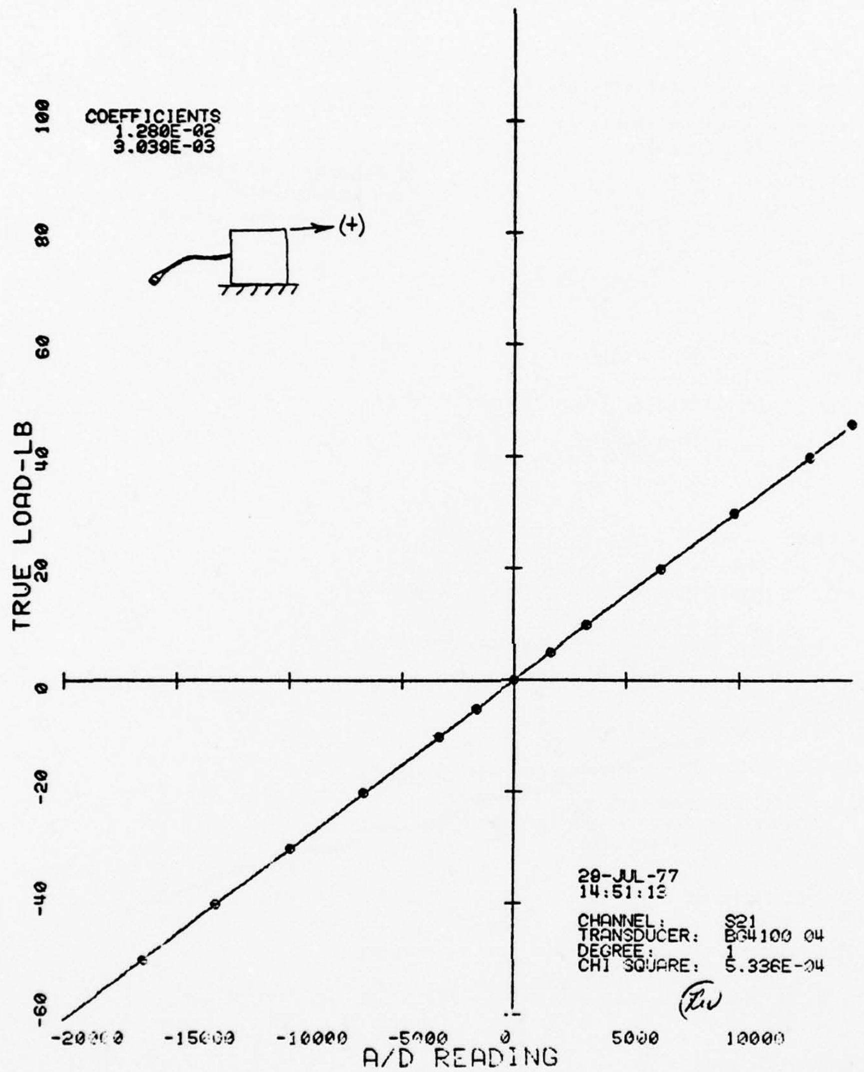

FIGURE IV-3 TRANSDUCER CALIBRATION DIALOG EXAMPLE

```
***********************************
***       WAVEMAKER SYSTEM      ***
***********************************
OLD OR NEW TEST > NEW
TEST # = 040
COMMAND LOGGING DESIRED > NO
AUTO TEST > NO
WILL A TANK BE USED > NO
    CHANNEL ID > S21
    CHANNEL NAME > BG4
    TRANSDUCER NAME > BG4100 04
    CHANNEL ID >
TST>LOAD
    MODE > NEW
    CHANNEL ID RANGE > S21
    LOAD > 0.0 LB

!!  FILE DPO:[50,4]BG4100 04.CDF;1 HAS  1 POINTS

        CALIBRATE TRANSDUCERS
        CHANNEL ID RANGE = S21 THROUGH S21
        LOAD =  0.000E-01 LB


    CHANNEL ID RANGE > S21
    LOAD > 10.0 LB

!!  FILE DPO:[50,4]BG4100 04.CDF;1 HAS  2 POINTS

        CALIBRATE TRANSDUCERS
        CHANNEL ID RANGE = S21 THROUGH S21
        LOAD =  1.000E+01 LB


    CHAN[illegible] RANGE > S21
    LOAD > [illegible]

!!  FILE DPO:[50,4]BG41[illegible]F;1 HAS  3 POINTS

        CALIBRATE TRANSDUCERS
        CHANNEL ID RANGE = S21 THROUGH S2[illegible]
        LOAD = -2.000E+01 LB


    CHANNEL ID RANGE > S21
    LOAD > -5.0

!!  FILE DPO:[50,4]BG4100 04.CDF;1 HAS 13 POINTS
        CALIBRATE TRANSDUCERS
        CHANNEL ID RANGE = S21 THROUGH S21
        LOAD = -5.000E+00 LB


    CHANNEL ID RANGE >
TST>DISP
    CHANNEL > S21
    DEGREE > 1
    HARD COPY > NO
TST>CDT TI:
```

NOTES:
(1) Operator responses are underlined
(2) ↲ = carriage return

FIGURE IV-4 TRANSDUCER CALIBRATION PLOT EXAMPLE

a) Hardware Setup and Activation

b) Data Retrieval and Storage

c) Test Monitoring

Due to the fact that synchronization of various portions of the execution is critical to the success of a test, the execution of a run is not under direct operator control. The actual run of the test will be under computer control and will be executed automatically according to the information input during the setup phase. The ACQUIRE verb can be used to merely acquire data without running the carriage.

Following the acquisition of data, the raw input data is demultiplexed, error checked, converted, and filed in system files for use during the analysis phase.

The objective of the test execution process is to collect test related data, error check and convert it to engineering units, store it in usable form for subsequent analysis, and to do all this in a reasonable amount of time. The time factor will have a very important effect on the design in determining how all the above processing will be accomplished.

IV-5.1 Hardware Setup and Activation

During the hardware setup phase, the multiplexer is loaded with the channel addresses to be scanned and the total number of channels to be scanned. The data frame generator is loaded with variable data and the frame rate is set. The DMA channels are set up as desired. Once setup is complete, the wavemaker is started (if necessary), a wait period is initiated to allow the wave spectrum to

develop, the high density digital tape recorder is started (if necessary), another wait period is inititated to allow the HDDR to get up to speed, the carriage is started, data acquisition will be initiated.

IV-5.2 Data Retrieval and Storage

Data retrieval and storage is basically the supervision of data flow from the DMA to the DISK.

The task of the processor then is fourfold:

a) create double buffers of sufficient size to handle the throughput to the disk memory,

b) issue read requests to the DMA channels to read sufficient data to fill a buffer,

c) issue disk writes in sufficient quantity to keep ahead of the input and

d) manage the switching of the double buffers such that one is filling and one is emptying as necessary.

All raw test data is stored on an unstructured disk file. Due to the critical speeds required, the file services of RSX-11 are not used to write the data buffers to disk. The second disk (DP1) is used primarily to hold the large raw data buffers and processor work space.

Due to the limitations of the capacity of the disk and the need to process the data from a test run in a reasonable amount of time, the maximum amount of data that can be collected for a single test run is 9×10^6 words.

If the HDDR is specified by the operator to record the data for the test run, the processor will store the time code generator reading when the HDDR interrupts the computer with the status that it is up to speed. This time will be used to specify the start time for the subsequent tape search.

IV-5.3 Test Monitoring

During the actual execution of the test run, the carriage control interface will be monitored for emergency information. If any emergency conditions become active, the interface will interrupt the computer. The processor will read the status word and take appropriate action.

IV-5.4 Post Run Data Processing

Once the data has been received and buffered on disk and test completion has occurred, this processor is activated. This processor has several functions to perform:

- o Demultiplex Input File(s)
- o Error Check Data (parity)
- o Input File Truncation
- o Convert Raw Data to Engineering Units
- o Adjust Converted Data for Cross Talk if Necessary

The first post run processing is that of demultiplexing the raw data file. This is a straight forward process of rearranging the data structure into n single dimensioned tables from the n x m two-dimensional input format (n = # of channels, m = # of samples).

During the demultiplexing operation, several error checks are

made. The first check made is to verify that frame numbers are continuous. A certain tolerance will be allowed at the beginning of the raw buffer. As long as the first frame is within one second of frame 0, processing will continue. Beyond that, the run will be aborted. Once into the data for the run, the following conditions will abort the run:

a) frame number lower than the previous frame,

b) gap in frame numbers larger than two frames, or

c) more than 15 gaps in the frame count of two or less frames.

The data from the missing frame(s) will be estimated by a simple linear interpolation from the last value in the last good frame to the first value in the next good frame for each channel. The next level of error checking is done at the data level. The hardware performs a parity check and sets the parity indication in the data word if a parity error is detected. Sensing the parity bit set will cause the data to be replaced by the average of the previous point and the next point for a particular channel. The encountered error levels are maintained and at the end of the conversion cycle the number of each type of error is logged to the operator. The log will specify the number of frame count errors on a per ADC (HSC,LSC,SHORE) basis, and the number of parity errors on a per data channel basis.

The Input File Truncation processor will allow the operator to specify, in seconds, the start and stop time between which input data is to be saved. The times will be considered to be

referenced to the start of the input time series. In this way, the data can be successively truncated, if necessary. Once specified, all input time series will be truncated by the indicated times. Truncation can be performed on either the raw input time series or after conversion on the engineering unit time series. Prior to conversion, the system will ask the operator if he wants to truncate the data. If not, conversion will proceed. In general, it is recommended that truncation be performed prior to conversion to save time from needless conversions.

Conversion of the raw input data into engineering units is done using a polynomial whose order and coefficients are a function of the last calibration performed on the particular transducer. Using the order and coefficients, the conversion routine will convert the input data. If any of the measurements were made using mechanically coupled transducers, the results must be adjusted for cross talk. The GANG command identified all such channels during test setup. While the processing is straightforward, it has a tendency to be time consuming. Two factors play an important role in the time required to accomplish this adjustment:

1. Length of input data table
2. Number of ganged transducers in dynamometer

As the size of the data increases, the adjustment time increases linearly. But as the number of ganged transducers increases, the adjustment time goes up much faster than linearly.

Finally, using the information input via the TEMP command, the channel measuring temperature is activated and three

seconds of temperature data are input, averaged, and stored in the run time file.

IV-6 TEST ANALYSIS

Corresponding to each automated test implemented in the wavemaker system, there is a Test Analysis Supervisor. Currently, these supervisors are:

- o PLN - Planing Boat Test
- o SEA - Seakeeping Test
- o EHP - Effective Horsepower Test
- o SHP - Self-Propelled Model Test
- o ACU - Acoustic Test

These supervisors facilitate the analysis of a test. Generally, a test proceeds as follows:

1) The operator prepares the model for testing and mounts it with its associated dynamometry under the appropriate carriage.

2) Via the DECwriter, the operator performs the normal test setup sequence, using the nouns and verbs described in this document.

3) The operator checks out the calibration of the transducers, and recalibrates them as necessary. He also performs any necessary zeroing of transducers.

4) When satisfied that the system is ready, the operator types the verb RUN to execute a run of the test. RUN causes the waveboard (for tests in waves), the HDDR, the carriage, the DMA channels, and the ADCs to be started in the proper sequence (see section IV-5). Data are acquired and automatically converted to engineering units. The timing to

the start of the next run begins when the carriage stops at the end of the tank, after returning.

5) When the run has ended, the operator may display any of the data time histories on the CRT, and truncate, filter, or decimate the time histories as he desires.

6) The operator now invokes a Test Analysis Supervisor, which causes the computer to enter the test analysis mode.

7) The computer then requests entry of parameters specific to the test.

8) The computer proceeds to calculate and store a predetermined set of intermediate results.

9) At this time, the operator may do additional analysis of the input data via the computational utilities, request non-report quality, quick-look plots or tabulations, or save the input data for later analysis (original input data are deleted when the next RUN verb is issued).

10) Operator now returns to Step 3 for the next run.

11) Following any run, normally after the last run, the operator can request the report quality plots and tabulations. When the output is complete and the operator wishes to end the test, he may save any data he wishes to save and type ENDT, causing all original test data to be deleted.

IV-7 DYNAMOMETER INTERFACE MODULES

Since data may be acquired via a number of different towing dynamometer systems, and, in some cases, via the gravity towed system, the data must be converted to a common format before it can be analyzed by a Test Analysis Supervisor. This conversion is performed by a dynamometer interface module. One module is included for each dynamometer in the system. The operator will identify the towing dynamometer to be used in the test during the test setup sequence, and its name will be stored in the run time file. This will allow the corresponding dynamometer interface module to be invoked at data analysis time. Currently, interface modules exist for the following dynamometers:

- o Pitch and heave dynamometer, 120 ft tank
- o Planing boat dynamometer, 120 ft and 380 ft tank
- o Surface-effect ship dynamometer, 380 ft tank
- o Seakeeping dynamometer, 380 ft tank

Each of these dynamometers comprises a particular configuration of hardware to attach a model ship to the towing carriage, and allows the model freedom in some components of motion while constraining others. Since the dynamometers do not measure some of the components of motion directly, geometric conversion formulas are required in those cases to produce the components of motion from the parameters actually measured. The concept of dynamometer interface tasks removes the restriction that a dynamometer be associated with a particular test (such as the EHP test), and permits any of the dynamometers to be used with any test.

IV-8 SYSTEM DATA BASE

The System Data Base provides the system with a standard, centralized vehicle for storage and retrieval of system data and a centralized method of task communications.

It consists of information within four areas:

- o Global Event Flags
- o Wavemaker Global Common
- o SEND/RECEIVE Buffers
- o FCS-Managed Files

As such, a consistent design concept is required for management, maintenance, and use of this data base. In order to maintain consistency in the system and in order to make maximum use of the functions of the operating system, the management of the files portion of the data base is handled by the File Control Services (FCS) of RSX-11D through adherance to a rigid naming convention. This subsystem provides a highly flexible data filing system and supports all standard DEC peripheral devices (disks, mag tape, etc.).

The basic flow into and out of the file data base is shown in Figure IV-5.

By using the FCS capabilities a standard file structure is maintained throughout the data base. In addition,

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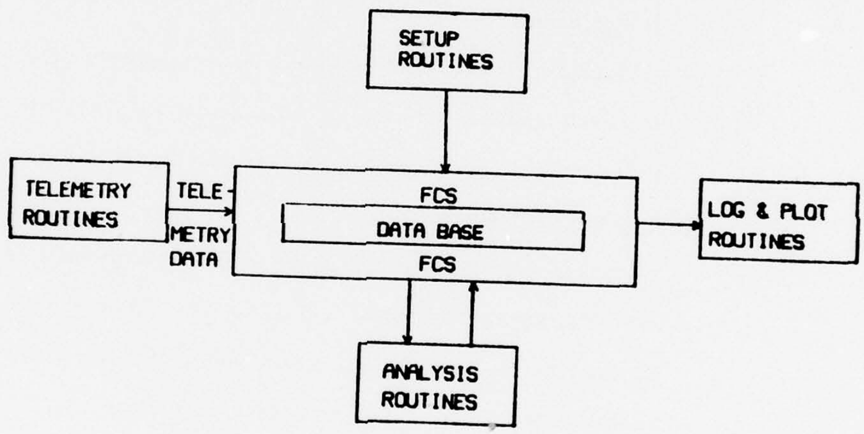


FIGURE IV-5 DATA BASE FLOW DIAGRAM

tasks need only know the filename of the data they need and not its location or other file information. All files, in addition to the header imposed on them by the FCS, have a Wavemaker Standard Header (WSH). This header contains information about the data in the file (integer/real, length, etc.).

Files reside on both disks, but certain restrictions are placed on usage of the second disk.

In addition to the data files, there are additional elements to the System Data Base:

- <u>Global Common</u>

  A Sharable Global Area (SGA) contains <u>system</u> related data. The data contained in the Global Common is available to all tests and is not connected to any one test.

- <u>SEND/RECEIVE Buffer</u>

  Tasks can communicate up to 255 words to another task via the SEND/RECEIVE capability in RSX-11D. This capability is used extensively in the Wavemaker system to communicate test related information from task to task.

- <u>Run Time File (RTF)</u>

  The RTF contains individual test related data. At the start up of a test, an RTF will be created for that specific test. Access to and contents of the RTF will be discussed later in this document. The RTF is a central source for test descriptive information and as such, it is used by all test processors. The system design centers around the concept

that there are a set of general test processors (setup, data acquisition, analysis, results, etc.) that can be employed in various combinations to perform specific tests. Therefore, a test processor, when called, first identifies which test it is executing, via information in the SEND mode, and then accesses the RTF for this test to determine the specifics of this test. In this way, many tests can be in progress, in various stages, with no risk that information for one test can get mixed up with information from another test.

The data (telemetered data, results, etc.) for a specific test are stored in files whose names contain information unique to that test number.

The RTF for a test is maintained until the test is ended (via an ENDT command). The RTF remains intact, even when the test it represents is suspended.

- <u>Global Event Flags</u>

  Tasks can communicate "event" information to other tasks via the global event capability of RSX-11D. In this way, a task can be activated or resumed when some system event occurs.

REFERENCES

1. Anderson, C. And Johnson, B., "A Computer Controlled Wave Generation System", 18th American Towing Tank Conference, August, 1977.

2. Gebhardt, J. C. and Martin, D. J., "AUTOTANK, An Automated Towing Tank Data Acquisition and Analysis System", CADCOM, Inc. Report No. 74-25, March, 1974.

3. Williams, S., "O/I Language Definition", CSC Document SD-OILANG-24, January 11, 1976.

APPENDIX A

EHP TEST Example

The following dialog and output was obtained during the execution of a still water EHP test of a 5 ft long destroyer-type model running in the 120 ft tank using the powered carriage. All operator inputs are underlined.

```
**
**      THIS IS AN EHP TEST IN STILL WATER
**
**              THE TEST IS SETUP TO PERFORM SETUP
**              COMMANDS FOR UP TO 3 CHANNELS OF DATA
**              (RTM.PTCH.HEAV) AND THEN TO ENTER
**              A LOOP (UP TO 200 ITERATIONS) TO PERFORM
**              EHP RUNS AND ANALYSIS.
**
**      THE SETUP PHASE
**
DYN
CHAN .RTM.120RES/.PTCH.120PIT/.HEAV.120HEV/.TEMP.PROBE
OI
WAIT 2 MIN
DRUN RUN1..25KTS..5FPSS.1MIN.NO.BOARD
DRUN RUN2..5KTS..5.1MIN.NO.BOARD
DRUN RUN3..75KTS..5.60.NO.BOARD
DRUN RUN4.1.0KTS..5.60.NO.BOARD
DRUN RUN5.1.25KTS..5.60.NO.BOARD
DRUN RUN6.1.5KTS..5.60.NO.BOARD
DRUN RUN7.1.75KTS..5.60.NO.BOARD
DRUN RUN8.2.0KTS..5.60.NO.BOARD
DRUN RUN9.2.25KTS..5.60.NO.BOARD
DRUN RN10.2.5KTS..5.60.NO.BOARD
DRUN RN11.2.75KTS..5.60.NO.BOARI
DRUN RN12.3.0KTS..5.60.NO.BOARD
DRUN RN13.3.25KTS..5.60.NO.BOARD
DRUN RN14.3.5KTS..5.60.NO.BOARD
SEQ RUN4.NONE/RUN5.NONE/RUN6.NONE/RUN7.NONE/RUN8.NONE/RUN9.NONE/RN10.NONE
SEQ RN11.NONE/RN12.NONE/RN13.NONE/RN14.NONE
INP S.ADC.OFF.ON.OFF
SCAN S.128.
**
**      ENTER LOOP TO DO MODEL RUNS
**
BEGL 200.YES
REZR
RUN
DCM RTM.EU.20.RTM.DCM
PLOT *.ON.*/RTM.DCM
EHPA
ENDL
EHPO
SUSP
```

identify dynamometer used & data channels (DYN, CHAN)

define runs, intervals, & run sequence (DRUN … SCAN)

BEGL ← *Begin loop of above defined model runs*

REZR ← *Rezero transducers*

RUN ← *Run model & acquire data*

DCM ← *Decimate*

EHPA ← *EHP analysis*

EHPO ← *EHP output routine*

LISTING OF AN AUTO TEST FILE; FILE NAME IS "EHPSW2"

```
MCR>HEL [102,1]
MCR>TST
```

← Sign On

Terminal Dialog During Execution of Auto Test

```
************************************
***      WAVEMAKER SYSTEM        ***
************************************
OLD OR NEW TEST > NEW
TEST # = 104
COMMAND LOGGING DESIRED > NO
AUTO TEST > YES
AUTO FILE NAME > EHPSW2
WILL A TANK BE USED > YES

    TANK ID > 120
    WATER DEPTH > 5.5
    TEMP CHAN > S13
    DRIVE >  POWR
AUT>**
AUT>**  THIS IS AN EHP TEST IN STILL WATER
AUT>**
AUT>**          THE TEST IS SETUP TO PERFORM SETUP
AUT>**          COMMANDS FOR UP TO 3 CHANNELS OF DATA
AUT>**                  (RTM,PTCH,HEAV) AND THEN TO ENTER
AUT>**                  A LOOP (UP TO 200 ITERATIONS) TO PERFORM
AUT>**                  EHP RUNS AND ANALYSIS.
AUT>**
AUT>**          THE SETUP PHASE
AUT>**
AUT>DYN
    DYNAMOMETER NAME > PLNDYN
AUT>CHAN ,RTM,120RES/,PTCH,120PIT/,HEAV,120HEV/,TEMP,PROBE
    CHANNEL ID 1 > 2\S23
    CHANNEL ID 2 > S25
    CHANNEL ID 3 > S24
    CHANNEL ID 4 >
$$  PARAMETER MAY NOT BE DEFAULTED
    CHANNEL ID 4 > S13
AUT>OI
TST>
SYS-ILLEGAL COMMAND
TST>AUTO
AUT>WAIT 2 MIN
AUT>DRUN RUN1,.25KTS,.5FPSS,1MIN,NO,BOARD
AUT>DRUN RUN2,.5KTS,.5,1MIN,NO,BOARD
AUT>DRUN RUN3,.75KTS,.5,60,NO,BOARD
AUT>DRUN RUN4,1.0KTS,.5,60,NO,BOARD
AUT>DRUN RUN5,1.25KTS,.5,60,NO,BOARD
AUT>DRUN RUN6,1.5KTS,.5,60,NO,BOARD
AUT>DRUN RUN7,1.75KTS,.5,60,NO,BOARD
AUT>DRUN RUN8,2.0KTS,.5,60,NO,BOARD
AUT>DRUN RUN9,2.25KTS,.5,60,NO,BOARD
AUT>DRUN RN10,2.5KTS,.5,60,NO,BOARD
AUT>DRUN RN11,2.75KTS,.5,60,NO,BOARD
AUT>DRUN RN12,3.0KTS,.5,60,NO,BOARD
AUT>DRUN RN13,3.25KTS,.5,60,NO,BOARD
AUT>DRUN RN14,3.5KTS,.5,60,NO,BOARD
AUT>SEQ RUN4,NONE/RUN5,NONE/RUN6,NONE/RUN7,NONE/RUN8,NONE/RUN9,NONE/RN1
```

```
!!  SOT GREATER THAN 77 WORDS (LENGTH=    10)
AUT>SEQ RN11,NONE/RN12,NONE/RN13,NONE/RN14,NONE
AUT>INP S,ADC,OFF,ON,OFF
AUT>SCAN S,128,
    CHANNEL # RANGE > S23-S25^U
23-25
AUT>**
AUT>**  ENTER LOOP TO DO MODEL RUNS
AUT>**
AUT>BEGL 200,YES
AUT>REZR
    CHANNEL NAME > RTM
    CHANNEL NAME > PTCH
    CHANNEL NAME > HEAV
    CHANNEL NAME >
AUT>RUN
    IS THIS AN ACOUSTIC TEST ? > NO
!!  RUN/WAVE VERIFICATION
!!  SEQUENCE #     1
!!  RUN ID = RUN4
!!  WAVE ID = NO WAVE
!!  ARE THESE ACCEPTABLE ? >
!!  SEQUENCE ACCEPTED
    CURRENT CARRIAGE POSITION (FT.) ? > 40
!!
!!  *** TYPE CTRL-X TO ABORT TEST MANUALLY ***
!!
!!  SETUP PROCESS INITIATED

PIP -- NO SUCH FILE(S)
DP1:[102,1]*.*;10400
!!  ACQUIRED TANK TEMPERATURE: 70.9 DEGF
VELOCITY FOR THIS RUN = 08        10
!!  RUN SUPERVISOR INITIATED
SUPV AT DEVINI
IAQID =    7115 IBC =     120
IAQID =    7115 IBC =     140
IAQID =    7115 IBC =     177
!!  SYSTEM IS READY
!! TYPE CARRIAGE RETURN TO PROCEDE OR CTRL+X TO ABORT
IAQID =    7115
IAQID =    7115
IAQID =    7115
IAQID =    7115
SUPV AT STRTUP
!!  RUN TERMINATED BY  CARRIAGE
!!  CARRIAGE STATUS AT RUN TERMINATION
      STOP (NORMAL) ACTIVATED
      CARRIAGE STOPPED STATUS
      SYSTEM IS NOT READY
      CARRIAGE NEAR WAVEMAKER
!!  RUN SUPERVISOR EXITING
!!  NUMBER OF FRAMES ACQUIRED TO FILE SHR2.RAW =    200
!!  FILE SHR2 HAD       0 TELEMETRY ERRORS AND  0 SKIPPED FRAMES
!!  SETUP EXITING
!!  TEST RUN COMPLETED !!
AUT>DCM RTM.EU,20,RTM.DCM
    PLOT *,ON,*/RTM.DCM
AUT>EHPA
    MODEL NAME > EEGZ
```

Diagnostic messages which will be deleted after system debug.

"

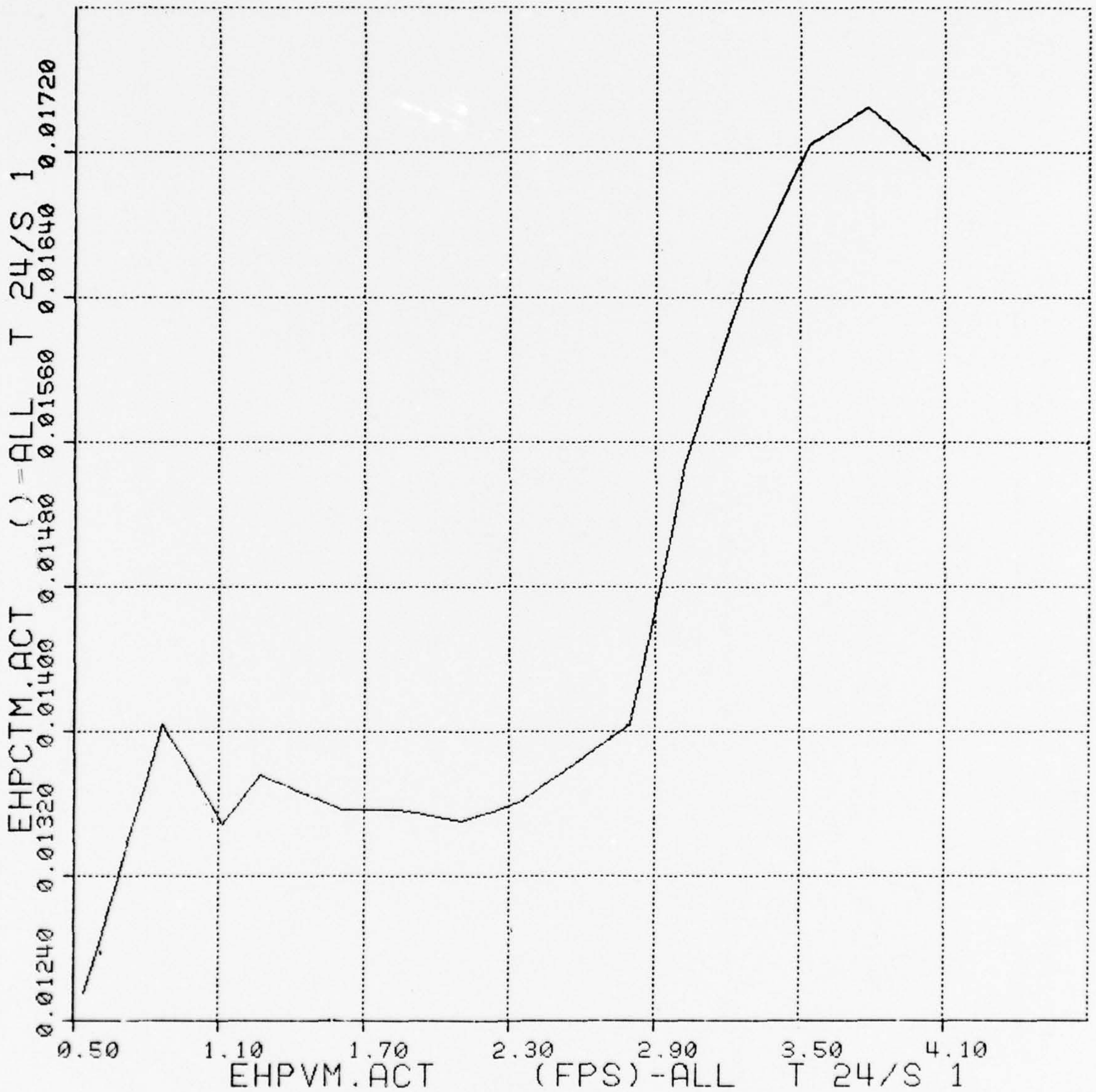
```
     PROCESSING MODE > SW
     DISPLACEMENT > 15.1
     STIMULATOR > STUDS
     WETTED SURFACE AREA > 3.54
     LENGTH ON WATERLINE > 5.1
     SAVE CTM FOR SHP TEST > NO
     LENGTH BETWEEN PERPENDICULARS > 5.1
     AMIDSHIPS TO LCG > -.5IN
     LENGTH OF TOWING LINK > 29.75IN
     AMIDSHIPS TO TOWING POINT > -.5IN
     INITIAL ANGLE BETWEEN TOWING LINK AND CARRIAGE > 45.77DEG
     ENTER INPUT CHANNEL NAMES:
     RESISTANCE CHANNEL NAME > THA1
     SURGE CHANNEL NAME >
     THETA 1 CHANNEL NAME > THA1
     THETA 2 CHANNEL NAME > THA1\2
     TRUNCATION DESIRED? > YES
     START TIME > 5.0
     STOP TIME > 25.0
AUT>ENDL
SYS-END OF LOOP ITERATION      1
TST>
AUT>REZR
     CHANNEL NAME >
AUT>RUN
TASK HIST CALLED BY RUN
CURRENT RUN NUMBER (I4) IRUNO =     1
CURRENT REPEAT RUN FLAG (I3) IRPTFL =    0     Diagnostic messages -
CURRENT RUN STATUS (I3) IRUNST =    0            to be deleted
RETURN STATUS (ISTAT) (I2) =
END OF HIST,SEND BACK TO CALLING TASK
!!  RUN/WAVE VERIFICATION
!!  SEQUENCE #     2
!!  RUN ID = RUN5
!!  WAVE ID = NO WAVE
!!  ARE THESE ACCEPTABLE ? > 40
!!  PLEASE ENTER 'YES' OR 'NO'
!!  ARE THESE ACCEPTABLE ? > YES
!!  SEQUENCE ACCEPTED
    CURRENT CARRIAGE POSITION (FT.) ? > 40
!!
!!  *** TYPE CTRL-X TO ABORT TEST MANUALLY ***
!!
!!  SETUP PROCESS INITIATED
!!  ACQUIRED TANK TEMPERATURE: 70.9 DEGF
VELOCITY FOR THIS RUN = 10       20
!!  RUN SUPERVISOR INITIATED
SUPV AT DEVINI
IAQID =    7115 IBC =     120                      "
IAQID =    7115 IBC =     140
!!  CARIAGE STATUS WORD # 1 ERROR(S) DETECTED
!!      MANUAL MODE
!!  TYPE CARRIAGE RETURN WHEN READY OR CTRL+Z TO ABORT THE RUN
!!  CARIAGE STATUS WORD # 1 ERROR(S) DETECTED
!!      MANUAL MODE
!!  TYPE CARRIAGE RETURN WHEN READY OR CTRL+Z TO ABORT THE RUN
IAQID =    7115 IBC =     177
!!  SYSTEM IS READY
!! TYPE CARRIAGE RETURN TO PROCEDE OR CTRL+X TO ABORT
```

```
!!   RUN TERMINATED BY  CARRIAGE
!!   CARRIAGE STATUS AT RUN TERMINATION
       STOP (NORMAL) ACTIVATED
       CARRIAGE STOPPED STATUS
       SYSTEM IS NOT READY
       CARRIAGE NEAR WAVEMAKER
!!   RUN SUPERVISOR EXITING
!!   NUMBER OF FRAMES ACQUIRED TO FILE SHR2.RAW =    160
!!   FILE SHR2 HAD       0 TELEMETRY ERRORS AND  0 SKIPPED FRAMES
!!   SETUP EXITING
!!   TEST RUN COMPLETED !!
AUT>DCM RTM.EU,20,RTM.DCM
AUT>PLOT *,ON,*/RTM.DCM
AUT>EHPA
     DO YOU WISH TO RE-ENTER MODEL PARAMETERS ? > NO
     TRUNCATION DESIRED? > YES
     START TIME > 4.0
     STOP TIME > 24.0
!!   UTIL : IBUF = *,     4.0000,   24.0000
SYS-END OF LOOP ITERATION      2
TST>
AUT>REZR
     CHANNEL NAME >
AUT>RUN
TASK HIST CALLED BY RUN
CURRENT RUN NUMBER (I4) IRUNO =     2
CURRENT REPEAT RUN FLAG (I3) IRPTFL =    0
CURRENT RUN STATUS (I3) IRUNST =    0
RETURN STATUS (ISTAT) (I2) =
END OF HIST,SEND BACK TO CALLING TASK
!!   RUN/WAVE VERIFICATION
!!   SEQUENCE #     3
!!   RUN ID = RUN6                                        ORT
!!   WAVE ID = NO WAVE
!!   ARE THESE ACCEPTABLE ? >
!!   SEQUENCE ACCEPTED
     CURRENT CARRIAGE POS
!!
!!   *** TYPE           ATUS RETURNED BY DATSUP = -4,    0
!!
!!   SE
          ERMINATED BY  CARRIAGE
      ARRIAGE STATUS AT RUN TERMINATION
       STOP (NORMAL) ACTIVATED
       CARRIAGE STOPPED STATUS
       SYSTEM IS NOT READY
       CARRIAGE NEAR WAVEMAKER
$$   SUPV; 25                                  TILT!
!!   RUN SUPERVISOR EXITING
##   CALSUP; 10
!!   TEST RUN WAS NOT SUCCESSFUL
$$   SETUP;  90
!!   SETUP EXITING
$$   RUN
SYS-TEST 104 SUSPENDED
SYS-SEEK ASSISTANCE FROM SYSTEMS PERSONNEL   !

**********************************
*** EXIT FROM WAVEMAKER SYSTEM ***
**********************************
```

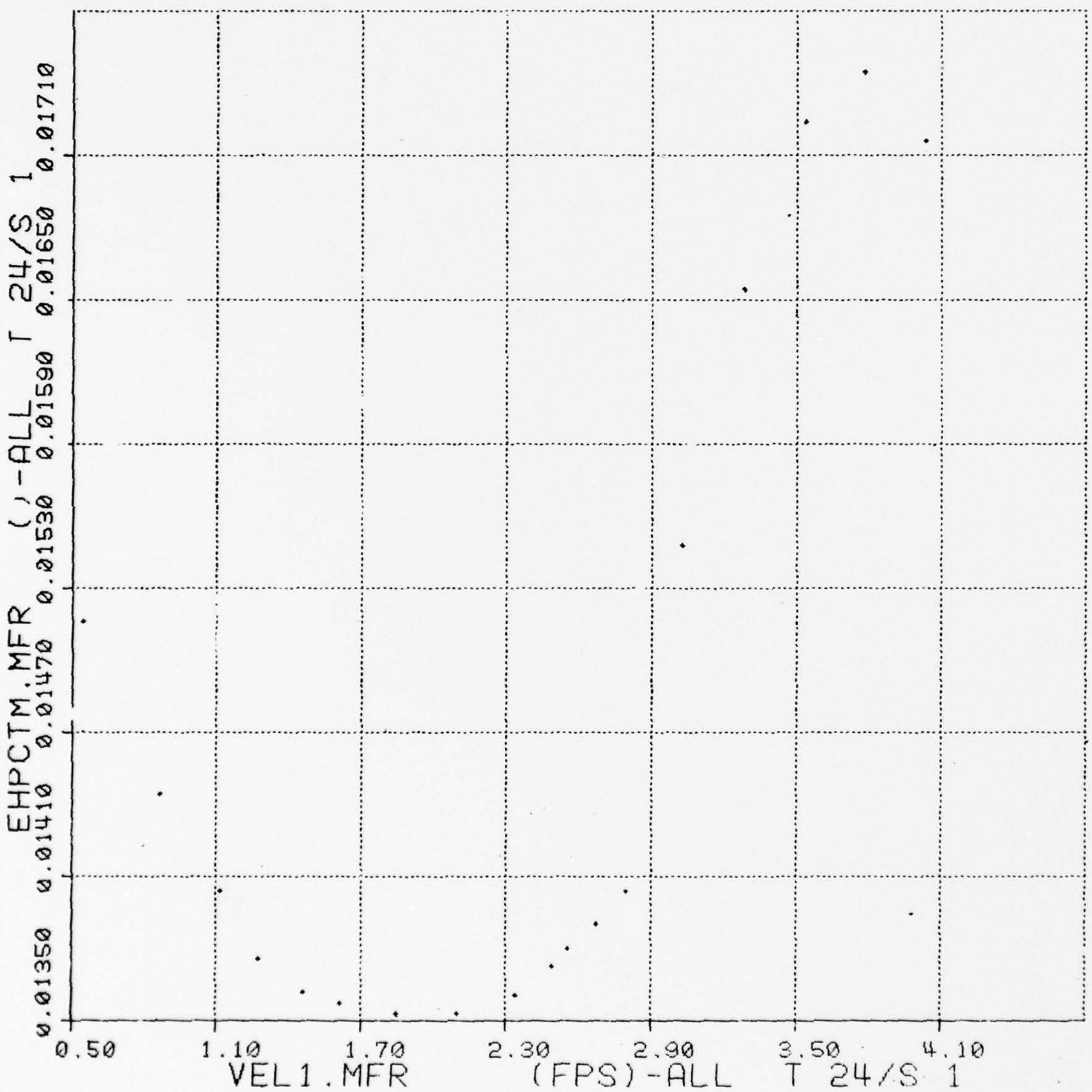
TEST: 24 RUN NO:25 DATE:18-AUG-77 TIME:11:44:18

Raw C_{t_m} vs. Model Speed in ft/sec. - points connected by straight lines. This is an example of a "quick look" plot.



TEST: 24 RUN NO:25 DATE:18-AUG-77 TIME:11:37:33

Manually faired C_{t_m} vs. Model Speed in fps.
This is a "quick look" plot.



USNA HYDROMECHANICS LABORATORY

MODEL DATA TABULATION

TEST NO.: 24 TEST TYPE: EHP. STILL WATER. 120, PC START DATE: 28-JUL-77 LOG DATE: 18-AUG-77, 11:26:06

MODEL NAME: LWL: 5.100 FT DISPLACEMENT: 15.1 LBS

WET SURFACE: 3.540 SQ FT LCG: -0.042 FT STIMULATOR:

RUN *	VM (KTS)	RTM (LBS)	FP RISE (FEET)	AP RISE (FEET)	TRIM (DEG)	FROUDE *	CTM -	RENLD *	CFM -	TEMP (F)
1	0.322	0.013	0.000	0.001	-0.01	0.042	0.1255E-01	0.2750E+06	0.6340E-02	73.3
2	0.513	0.036	-0.002	0.000	-0.01	0.068	0.1404E-01	0.4384E+06	0.5655E-02	73.3
3	0.663	0.058	-0.002	-0.001	-0.01	0.087	0.1348E-01	0.5670E+06	0.5323E-02	73.3
4	0.753	0.076	-0.003	-0.001	-0.02	0.099	0.1376E-01	0.6433E+06	0.5171E-02	73.3
5	0.955	0.121	-0.005	-0.002	-0.03	0.126	0.1357E-01	0.8165E+06	0.4901E-02	73.3
6	1.097	0.159	-0.007	-0.004	-0.03	0.145	0.1357E-01	0.9371E+06	0.4754E-02	73.3
7	1.244	0.204	-0.009	-0.006	-0.04	0.164	0.1351E-01	0.1063E+07	0.4626E-02	73.3
8	1.386	0.255	-0.010	-0.008	-0.02	0.183	0.1361E-01	0.1185E+07	0.4520E-02	73.3
9	1.510	0.307	-0.012	-0.010	-0.03	0.199	0.1380E-01	0.1290E+07	0.4438E-02	73.3
10	1.657	0.377	-0.014	-0.014	0.00	0.218	0.1404E-01	0.1417E+07	0.4352E-02	73.3
11	1.793	0.485	-0.014	-0.022	0.10	0.236	0.1548E-01	0.1533E+07	0.4281E-02	73.3
12	1.944	0.610	-0.011	-0.031	0.24	0.256	0.1654E-01	0.1662E+07	0.4210E-02	73.3
13	2.095	0.739	-0.004	-0.041	0.43	0.276	0.1724E-01	0.1791E+07	0.4146E-02	73.4
14	2.240	0.854	0.002	-0.047	0.58	0.295	0.1745E-01	0.1915E+07	0.4090E-02	73.3
15	2.390	0.950	0.006	-0.051	0.68	0.315	0.1716E-01	0.2044E+07	0.4037E-02	73.4

EHPO Tabulation of Model Scale Test Data
This is "report quality" output.

PAGE 1 OF 1

USNA HYDROMECHANICS LABORATORY
MODEL TEST RESULTS

TEST NO.: 24
TEST TYPE: EHP,SW ,120 PD

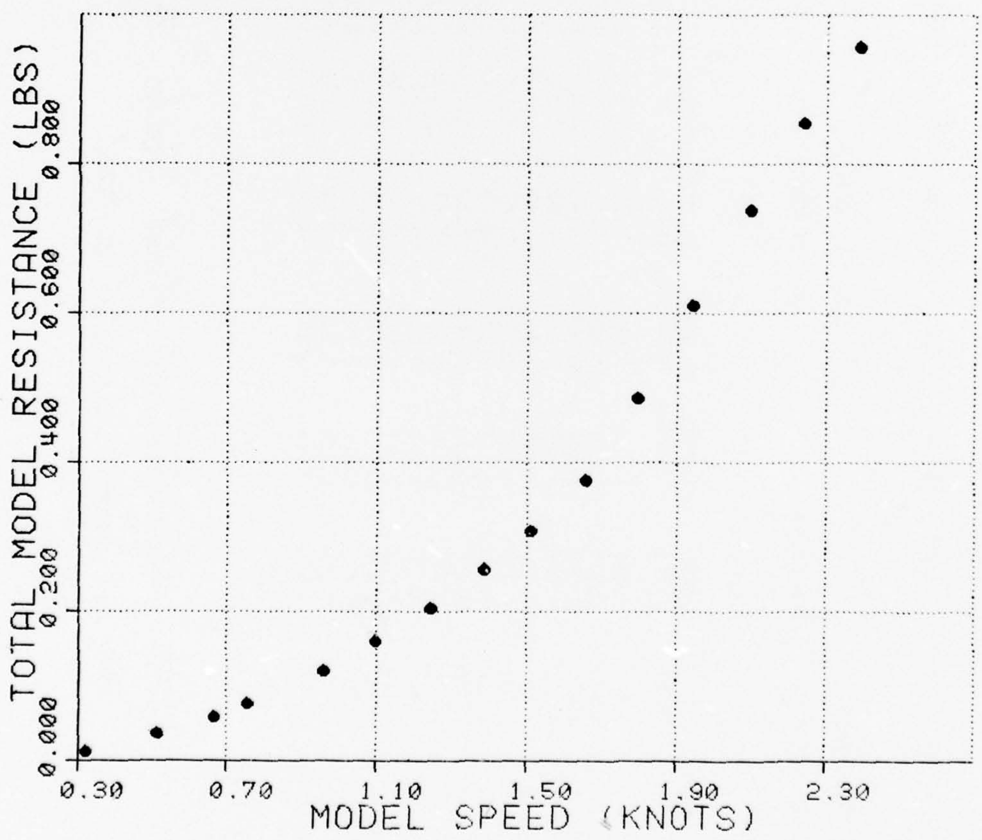
START DATE: 28-JUL-77 08:36:03
LOG DATE: 18-AUG-77 11:23:06

MODEL NAME:
DISPLACEMENT: 15.1 LBS
WET SURFACE: 3.5 SQ FT
WATER TEMP: 70.8 (F)

LWL: 5.10 FT
LCG: -0.04 FT
STIM:

TOTAL MODEL RESISTANCE(RTM)

EHPO Graphical Presentation - "Report Quality" Output



USNA HYDROMECHANICS LABORATORY
MODEL TEST RESULTS

TEST NO.: 24
TEST TYPE: EHP,SW ,120 PD

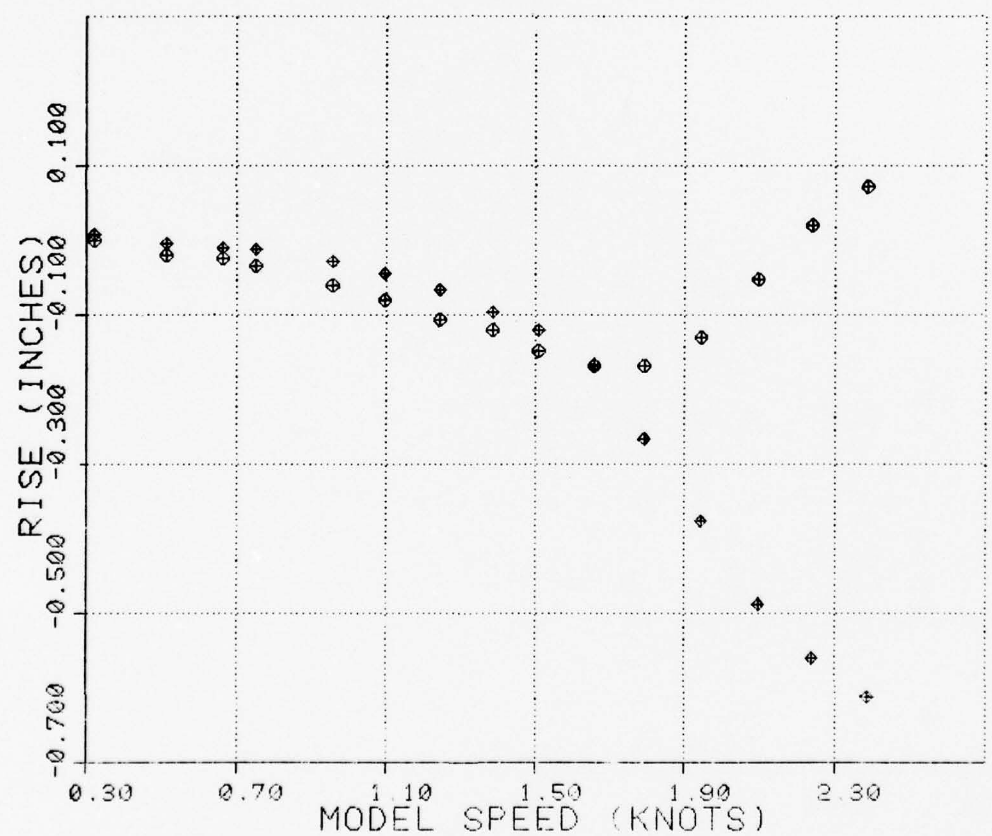
START DATE: 28-JUL-77 08:36:03
LOG DATE: 18-AUG-77 11:23:06

MODEL NAME:
DISPLACEMENT: 15.1 LBS
WET SURFACE: 3.5 SQ FT
WATER TEMP: 70.8 (F)

LWL: 5.10 FT
LCG: -0.04 FT
STIM:

LEGEND: ⊕=FP RISE ⊕=AP RISE

EHPO Plot of Model Sinkage & Trim.
"Report Quality" output.



USNA HYDROMECHANICS LABORATORY
MODEL TEST RESULTS

TEST NO.: 24
TEST TYPE: EHP,SW ,120 PD

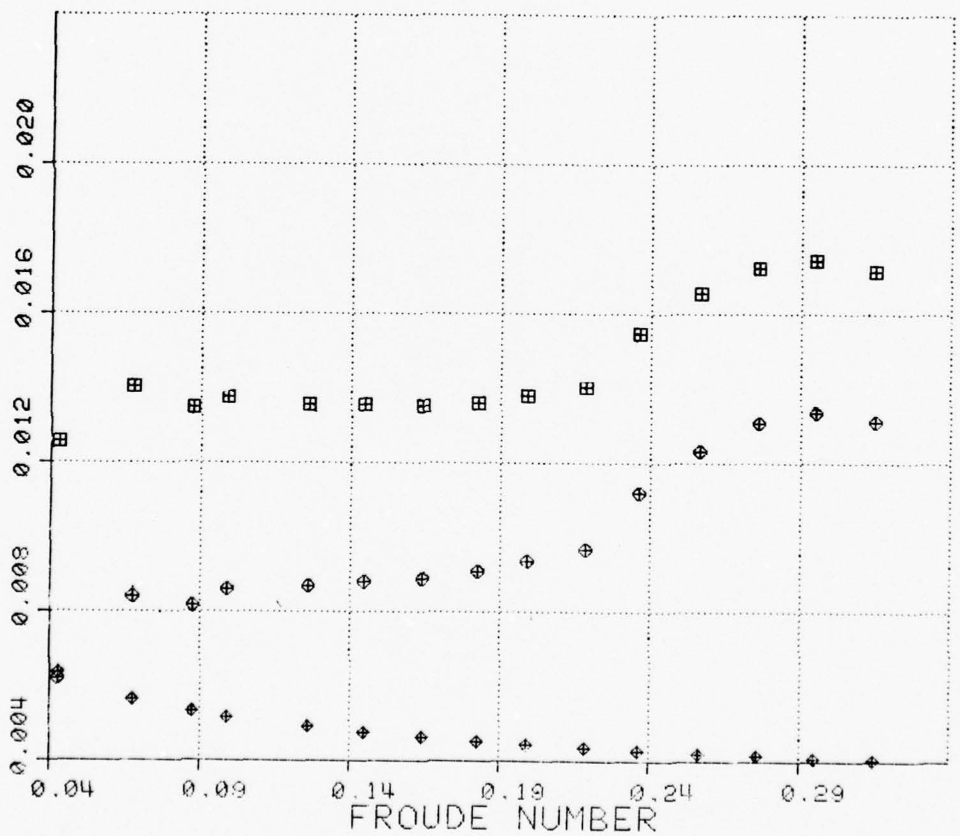
START DATE: 28-JUL-77 08:36:03
LOG DATE: 18-AUG-77 11:23:06

MODEL NAME:
DISPLACEMENT: 15.1 LBS
WET SURFACE: 3.5 SQ FT
WATER TEMP: 70.8 (F)

LWL: 5.10 FT
LCG: -0.04 FT
STTM:

LEGEND: ⊞ =CTM ⊕ =CFM ⊕ =CRM

EHPO Unfaired Resistance Coefficients vs. F_N - 'Report Quality' Output



USNA HYDROMECHANICS LABORATORY

PROTOTYPE SHIP EXPANSION

TEST NO: 24 TEST TYPE: EHP, STILL WATER, 120, PC START DATE: 18-AUG-77 LOG DATE: ,

MODEL NAME: LWL: 408.000 FT DISPLACEMENT: 3550.1 LTSW

WET SURFACE: 22656.000 SQ FT LCG: -3.333 FT WATER: 59.0 (F), SW

SCALE RATIO: 80.000 CORRELATION: 0.0004 ITTC

FROUDE #	VS (KTS)	EHP (HP)	FP RISE (FEET)	AP RISE (FEET)	CRS -	RENLD #	CFS -	CTS -	SPDLN (KTS/FT**0.5)
.042	2.88	43.	0.00	0.05	0.6213E-02	0.2599E+08	0.2558E-02	0.9171E-02	0.14
.068	4.59	213.	-0.13	-0.03	0.8389E-02	0.4142E+08	0.2377E-02	0.1117E-01	0.23
.087	5.93	447.	-0.16	-0.06	0.8161E-02	0.5358E+08	0.2285E-02	0.1085E-01	0.29
.099	6.73	676.	-0.23	-0.08	0.8588E-02	0.6080E+08	0.2242E-02	0.1123E-01	0.33
.126	8.55	1381.	-0.40	-0.19	0.8665E-02	0.7716E+08	0.2164E-02	0.1123E-01	0.42
.145	9.81	2110.	-0.53	-0.30	0.8817E-02	0.8857E+08	0.2120E-02	0.1134E-01	0.49
.164	11.13	3086.	-0.71	-0.44	0.8880E-02	0.1005E+09	0.2082E-02	0.1136E-01	0.55
.183	12.40	4334.	-0.80	-0.63	0.9086E-02	0.1119E+09	0.2050E-02	0.1154E-01	0.61
.199	13.50	5724.	-0.99	-0.80	0.9362E-02	0.1219E+09	0.2025E-02	0.1179E-01	0.67
.218	14.82	7765.	-1.13	-1.11	0.9692E-02	0.1339E+09	0.1998E-02	0.1209E-01	0.73
.236	16.03	11031.	-1.12	-1.78	0.1119E-01	0.1448E+09	0.1976E-02	0.1357E-01	0.79
.256	17.39	15230.	-0.87	-2.51	0.1233E-01	0.1570E+09	0.1954E-02	0.1469E-01	0.86
.276	18.74	20018.	-0.35	-3.25	0.1310E-01	0.1692E+09	0.1933E-02	0.1543E-01	0.93
.295	20.03	24848.	0.13	-3.73	0.1336E-01	0.1809E+09	0.1915E-02	0.1568E-01	0.99
.315	21.37	29689.	0.47	-4.08	0.1312E-01	0.1930E+09	0.1898E-02	0.1542E-01	1.06

EHPO Tabulation of Expanded (Ship Scale) Data
("Report Quality" output)

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USNA HYDROMECHANICS LABORATORY
PROTOTYPE SHIP EXPANSION

TEST NO.: 24
TEST TYPE: EHP,SW ,120 PD

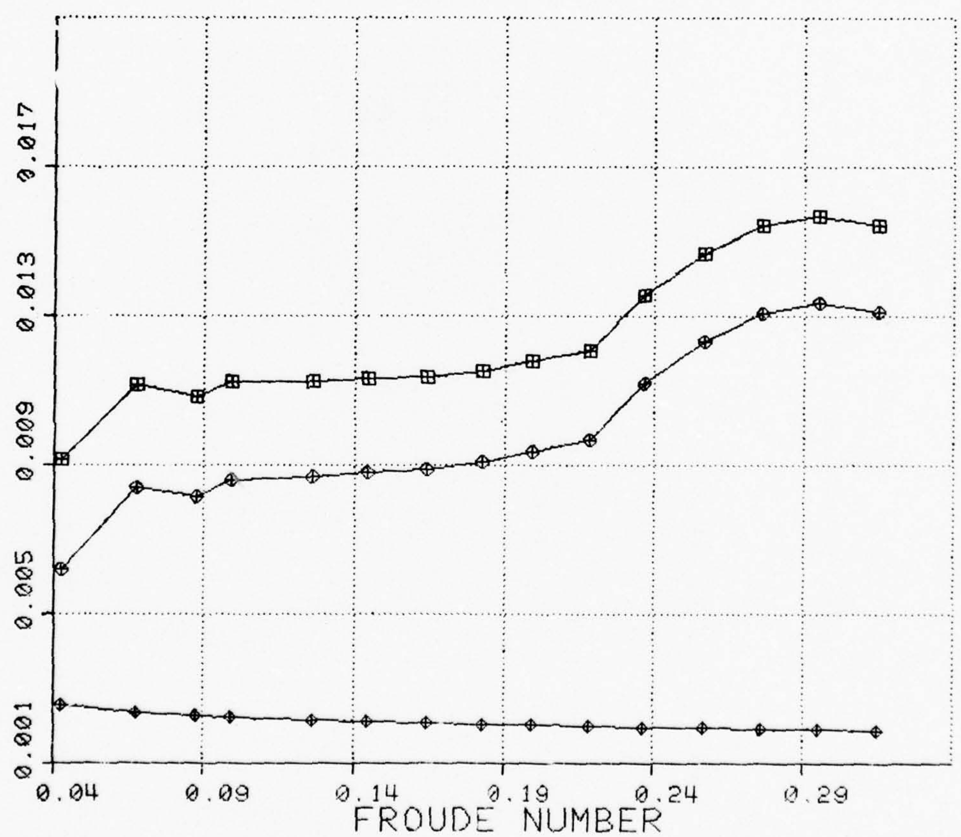
START DATE: @@@@@@@@@ @@@@@@@@
LOG DATE: @@@@@@@@@ @@@@@@@@

MODEL NAME:
DISPLACEMENT: 3451.4 LTSW
WET SURFACE: 22656.0 SQ FT
SCALE RATIO: 80.00

LWL: 408.00 FT
LCG: -3.33 FT
CORRELATION: 0.0004 ITTC
WATER: SALT

LEGEND: ⊞ =CTS ⊕ =CFS ⊕ =CRS

EHPO Ship-Scale Resistance Coefficients vs. F_N
("Report Quality" output)



USNA HYDROMECHANICS LABORATORY
PROTOTYPE SHIP EXPANSION

TEST NO.: 24
TEST TYPE: EHP,SW ,120 PD

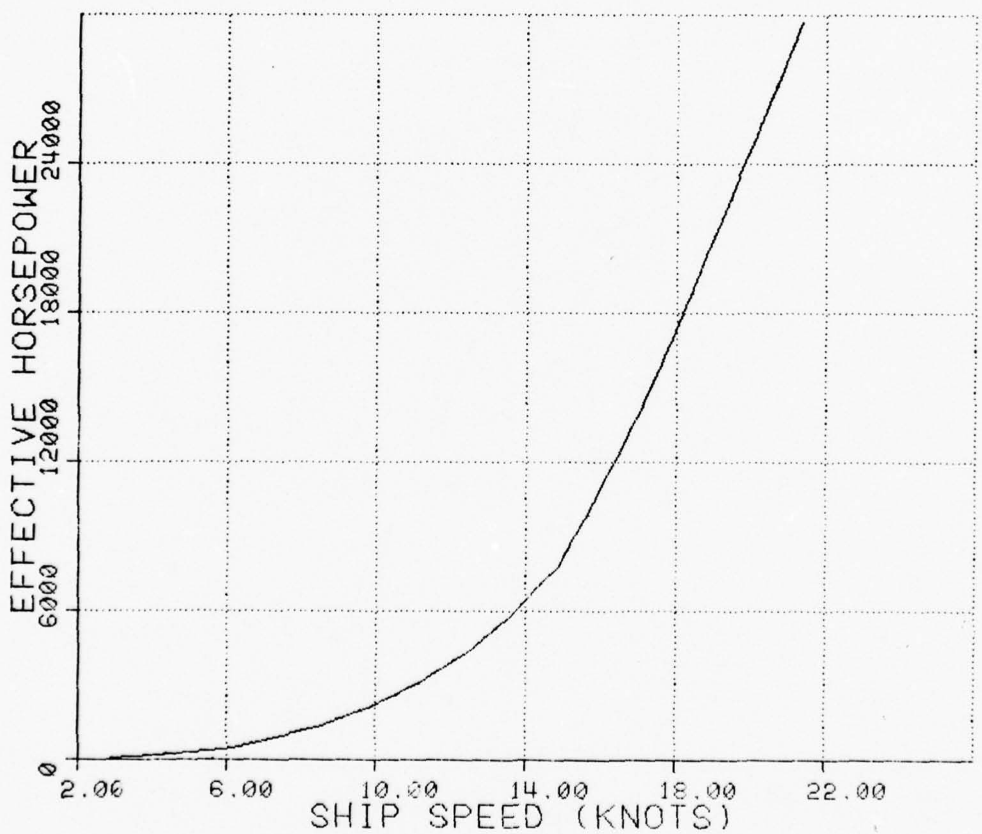
START DATE: @@@@@@@@@ @@@@@@@@
LOG DATE: @@@@@@@@@ @@@@@@@@

MODEL NAME:
DISPLACEMENT: 3451.4 LTSW
WET SURFACE: 22656.0 SQ FT
SCALE RATIO: 80.00

LWL: 408.00 FT
LCG: -3.33 FT
CORRELATION: 0.0004 ITTC
WATER: SALT

PROTOTYPE SHIP EFFECTIVE HORSEPOWER

EHPO Graphical Output - with Computed Points Connected - "Report Quality" Output



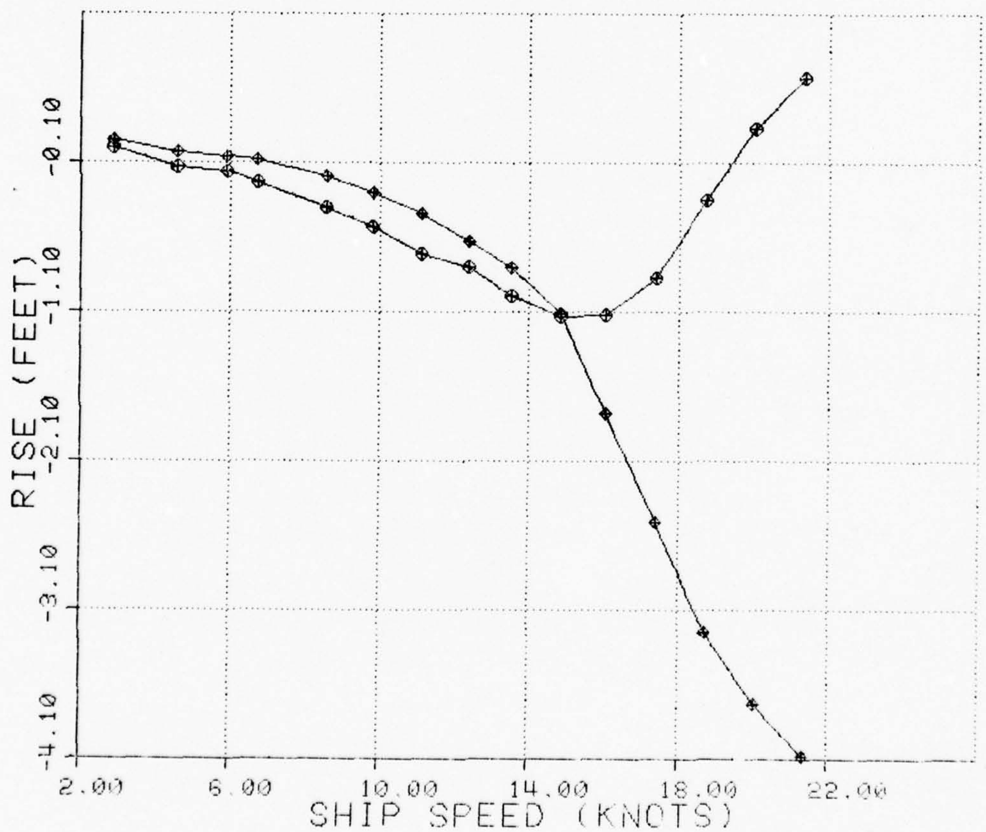
USNA HYDROMECHANICS LABORATORY
PROTOTYPE SHIP EXPANSION

TEST NO.:	24	START DATE:	@@@@@@@@@ @@@@@@@@
TEST TYPE:	EHP,SW ,120 PD	LOG DATE:	@@@@@@@@@ @@@@@@@@

MODEL NAME:			LWL:	408.00	FT	
DISPLACEMENT:	3451.4	LTSW	LCG:	-3.33	FT	
WET SURFACE:	22656.0	SQ FT	CORRELATION:	0.0004	ITTC	
SCALE RATIO:	80.00		WATER:	SALT		

LEGEND: ⊕=FP RISE ⊕=AP RISE

EHPO Ship Scale Graphical Output
("Report Quality")



APPENDIX B

Summary of COMMANDS

The following is an alphabetical list of commands currently available in the system. Parameter lists have been eliminated for the purpose of brevity. If more complete descriptions of the commands are required, Reference 3 should be consulted.

- ACQ - ACQUIRE DATA - VERB

  This command will activate the acquire data processor. An optional parameter of the maximum number of data frames to acquire may be included. Data acquisition via the shore based ADC-DMA will be initiated and will continue until either the requested number of data frames is reached or ENDA or ABRT are entered.

- ACUA - ACOUSTIC TEST ANALYSIS - VERB

  The ACUA command invokes the ACUA supervisor, which computes the output spectra required for the Acoustic test.

- AMP - COMPUTE AMPLITUDE SPECTRUM -VERB

  The AMP command processor computes an amplitude spectrum of a PSD or an FFT file, or the square root of a CRS, RAO, or COH file. The output is a complex spectrum stored in magnitude-phase format.

- AUTO - RE-ENTER AUTOMATIC MODE -VERB

  This command allows a test to be switched back to automatic mode after some commands have been entered manually.

- BEGL - BEGIN COMMAND LOOP - NOUN

  This command is used to mark the beginning of a group of commands which are to be executed a number of times.

o CDAT - KEYBOARD ENTRY OF CALIBRATION DATA - VERB

CDAT has the same function as the LOAD command, except that the operator enters both the deadload values and the transducer response readings via the keyboard.

o CHAN - CHANNEL INFORMATION - NOUN

This command associates a name with a channel number. The name is stored in a table in the Run Time File and used by the Run processor to name files containing data from that channel. The name of the transducer which is attached to the channel is also provided by this command. The transducer name is used to obtain the calibration co-efficients to be used for correction of the data from the channel.

o CNLD -DEFINE CONVOLUTION KERNEL - VERB

Via the CNLD command, the operator may define a convolution kernel (filter) in the frequency domain. Executing CNLD will cause the computer to solicit entry of up to N frequency domain values of a filter function, where N, the filter length is a power of two in the range ($8 \leq N \leq 1024$). The operator may enter values, V, in the range ($0 \leq V \leq 1$).

o CNV - CONVOLUTION FUNCTION - VERB

The CNV command processor computes the non-circular convolution of the specified range of frames of the input time series with a user defined convolution kernel. The frame size used in the computation is the frame size of the convolution kernel. The output of the CNV processor is a real-valued time series whose length is one frame less than the number of frames of the input time series.

o COH - COHERENCE FUNCTION - VERB

The COH command processor computes the coherence function between the two input time series. If a range of frames is specified as the input, the result is an average over that range. The frame size, N, used in the operation is the spectral analysis frame size in force at the time the command is invoked. The output of the COH processor is a function consisting of N/2 complex points whose imaginary parts are zero.

o COOR - DEFINE PLOT COORDINATES -NOUN

This command specifies the coordinate system which will be used to display data by the PLOT command. The system specified by the command will be used until another COOR command is issued.

- COR - CORRELATION FUNCTION - VERB

  The COR command processor computes the non-circular correlation function of two input time series. If a range of frames is specified, the cross spectra of each corresponding pair of frames are averaged together and the correlation function is obtained by inverting this average. The output of the COR processor is a real-valued series whose length is equal to the current spectral analysis frame size.

- CRS - CROSS SPECTRUM -VERB

  The CRS command processor computes the cross spectrum of two time series. If a range of frames of the input data is specified, the result will be the average of the cross spectrum of each pair of input data frames. The frames size, N, used in the operation is the spectral analysis frame size in force at the time the command is invoked. The output of the CRS processor is a spectrum consisting of N/2 complex frequency estimates.

- DAC - DAC CONFIGURATION - NOUN

  This command is used to have one of the data measurements in a frame displayed on the DAC of an acquisition system.

- DCM - DECIMATE A TIME SERIES - VERB

  Via the DCM command, the operator may form a new time series consisting of each ith point of the input time series. DCM may be used after digital filtering to reduce the length of a time series by deleting the redundant points.

- DISK - CREATE PERMANENT DISK FILE - VERB

  This command is used to save a disk file so it will not be deleted at the end of a test. The user specifies the name of the file to be saved as well as the name the file is to be saved as. If the user specified a UIC in the filename for the saved file, the file will be saved there. If not, the UIC will default to [50, 1].

- DISP - DISPLAY CALIBRATION CURVE - VERB

  Invoking DISP causes display of the calibration data points along with a fitting polynomial of specified degree, and the chi square goodness of fit statistic. Hard copy of this display may also be obtained.

- DOUT - OUTPUT FILE TO DAC -VERB

  The specified file is output to the DAC as described in the parameter list.

- DRUN - DEFINE A RUN - NOUN

  This command associates a set of run parameters with a name. The name is then used in a SEQ command to indicate that those parameters are desired.

- o DYN - DYNAMOMETER IDENTIFICATION - NOUN

This command identifies the dynamometer that is to be used for the test. It is used by the analysis processors to determine what transformations must be applied to input data to yield the desired results.

- o EHPA - EHP TEST ANALYSIS - VERB

The EHPA command invokes the EHPA supervisor, which computes the various model parameters, averages, spectra, phases and RAOs indicated by the operator specified test analysis mode (still water, regular wave, or irregular wave) and the available time histories. It stores the results pending their subsequent use by the EHP output supervisor (EHPO).

- o EHPO - EHP TEST OUTPUT - VERB

The EHPO command invokes the EHPO supervisor, which issues the EHP test report quality plots and tabular logs on the Versatec line printer.

- o ENDL - END COMMAND LOOP - NOUN

This command marks the end of a group of commands which are to be executed a number of times. This command causes SYSEX to return to the last BEGL command and start executing the commands after it again. The repeated execution of the commands will continue until the count specified in the BEGL command has been satisfied. If prompting was requested in BEGL, ENDL will indicate the end of each

iteration of the loop and will accept the following four requests at that time:

↵	-continue looping
SUSP:↵	-suspend test
ENDT:↵	-end the test
XITL:↵	-exit from the loop

o ENDT - END OF TEST - VERB

This command is used to indicate that the test is ready for termination. It causes all files which have not been saved by the DISK or TAPE command to be deleted, and terminates the test.

o ENDW - END WAVE CALIBRATION -VERB

This command causes the user to exit from wave calibration mode.

o FAIR - ENTER MANUALLY FAIRED DATA - VERB

Via the FAIR command, the operator may enter manually faired data into the computer.

o FFT - FORWARD FOURIER TRANSFORM OF REAL VALUED DATA -VERB

The FFT command processor performs a discrete forward Fourier transform of a frame (N points) of the specified data file. The result is a spectrum having N/2 complex frequency estimates. The frame size used in the computation is the spectral analysis frame size in force at the time the command is invoked.

o FIX - CREATE CALIBRATION POLYNOMIALS FOR TRANSDUCERS -VERB

The FIX command processor creates fitting polynomials of the degree specified for each of the designated transducers.

o FLT - FILTER A TIME SERIES - VERB

Via the FLT command, the operator may apply a digital band-pass filter to the input time series.

o FRAM - FRAME INFORMATION - NOUN

Information to be included in the headers of data frames coming from an acquisition system may be specified with this command. The information must be specified as octal numbers.

o GAND - DEFINE A GANGED TRANSDUCER - NOUN

The GAND command allows a group of up to seven transducers to be associated into a "gang" for purposes of removing crosstalk among their readings.

o GANG - GANGED TRANSDUCER IDENTIFICATION - NOUN

This command specifies that a ganged transducer which requires crosstalk correction is being used in the test. The ganged transducer is identified by the name which was assigned to it when it was defined by a GAND command.

o HAN - ENABLE/DISABLE HANNING - NOUN

Via the HAN command, the operator may enable or disable Hanning of time series data. When Hanning is enabled, all time series data are automatically Hanned prior to spectral analysis operations.

o HDDR - HDDR INPUT CONFIGURATION - NOUN

This command is used to describe the configuration of the HDDR when it is used as the data source for a run.

o HOUT - OUTPUT A FILE TO THE HDDR - VERB

The specified raw data file(s) are output to the HDDR as specified by the parameter list.

o HST - HISTOGRAM - VERB

The HST command processor computes the histogram of the input data set over the specified range of frames. The input data set may be a time series, a power spectrum, the magnitude portion of a RAO or the magnitude portion of a spectrum in magnitude squared-phase form.

o IFT - INVERSE FOURIER TRANSFORM - VERB

The IFT command processor performs an inverse Fourier transform on a spectrum consisting of N/2 complex frequency estimates. The result is a time series consisting of N real-valued data points. The frame size, N, used in the computation is the spectral analysis frame size of the input spectrum.

o INP - TEST DATA INPUT DEFINITION - NOUN

This command is used to specify the input configuration of the DMAs on an acquisition system, as well as the source of input to the acquisition system.

o LOAD - LOAD TRANSDUCERS AND COLLECT CALIBRATION DATA - VERB

The LOAD command initiates a computer-assisted procedure for the calibration of transducers. The operator specifies a set of deadload values for a group of transducers he wishes to calibrate, then the computer stores the average transducer readings in response to the deadload values. When a sufficient number of points for each transducer has been obtained, the operator may fit a calibration polynomial via the FIX command.

o LOG - OUTPUT TABULAR LOG - VERB

This command is used to output tabular logs of data files to the printer, DECwriter, or a CRT. Up to three files may be logged versus a single independent variable on a CRT, and up to six files may be logged versus a single independent variable on the printer of DECwriter.

o MAN - ENTER MANUAL MODE - VERB

This command, when included in an automatic test file, causes a switch to manual mode, allowing commands to be entered from the DECwriter.

o MNTR - MONITOR TIME SERIES ANALYSIS COMPUTATIONS ON THE TEKTRONIX DISPLAY - NOUN

This command is used to request the contents of the result buffer of the Macro Arithmetic Processor (MAP) unit to be displayed on the Tektronix CRT. The MAP result buffer normally contains the intermediate and final results of a time series analysis computation. Consequently, the operator may, as a function is being computed, see the result take form. The four options which may be used with the MNTR command allow the operator to display all points of the result buffer (for results in the time domain), to display only the odd or even numbered points (for results in the frequency domain) or to turn off the display.

o OFF = turn off the display

hold time = the time the present intermediate result is displayed before proceeding to the next. If omitted, the hold time defaults to zero.

o MPH - CONVERT TO MAGNITUDE SQUARED-PHASE FORM -VERB

The MPH command processor produces a magnitude squared-phase format spectrum given a real-imaginary spectrum as input.

- MRUN - MANUAL EXECUTION OF A RUN - VERB

  This command activates the MRUN processor allowing the selection of a run/wave combination at the time of the run.

- PAGE - CRT PLOT PAGE DEFINITION - NOUN

  This command is used to define a page size and time interval for plots to a CRT.

- PLNA - PLANING BOAT TEST ANALYSIS -VERB

  The PLNA command invokes the Planing Boat test analysis supervisor, which computes the various model parameters, averages, spectra, phases, and RAOs indicated by the test analysis mode specified by the operator (still water, regular wave, or irregular wave) and the available time histories. The results are stored pending their subsequent use by the Planing Boat output supervisor (PLNO).

- PLNO - PLANING BOAT TEST OUTPUT - VERB

  The PLNO command invokes the PLNO supervisor, which issues the Planing Boat test report quality plots and tabular logs on the Versatec line printer.

- PLOT - PLOT SYSTEM DATA - VERB

  This command is used to output graphical plots to either the plotter or a CRT. Up to three files may be plotted versus a single independent variable.

- PSD - POWER SPECTRAL DENSITY - VERB

  The PSD command processor computes the power density spectrum of the input time series. If a range of frames is specified as the input, the PSDs of the individual frames are averaged together to form the result. Averaging over several frames has the effect of stabilizing the spectrum (if the data is self-stationary), but does not remove noise. The frame size, N, used in the operation is the spectral analysis frame size in force at the time the command is invoked. The output of the PSD processor is a spectrum consisting of N/2 complex points whose imaginary parts are zero.

- RAO - RESPONSE AMPLITUDE OPERATOR -VERB

  The RAO command processor computes the Response Amplitude Operator relating the two input time series. If a range of frames is specified, the result will be the average of the Response Amplitude Operators computed from each pair of input data frames. The frame size, N, used in the operation is the spectral analysis frame size in force at the time the command is invoked. The output of the RAO processor is a spectrum consisting of N/2 complex frequency estimates in magnitude squared-phase form.

- RECD - HDDR RECORD CONFIGURATION - NOUN

  This command is used to specify the HDDR configuration when data from the ADCs are to be recorded during a test.

- RELY - DEFINE RELAY OUTPUTS - NOUN

  This command is used to specify the values that are to appear on the relay bits which are output to the carriages when they reach steady state velocity.

- REZR - PERFORM REZERO - VERB

  This command will activate the rezero processor permitting redefinition of a transducer's "Y" intercept.

- RIM - CONVERT TO REAL-IMAGINARY FORMAT - VERB

  The RIM command processor produces a real-imaginary format spectrum given a magnitude squared-phase format spectrum as input.

- RNGE - SET RANGE FOR PLOT OR LOG - NOUN

  This command is used to specify a range of interest for a PLOT or LOG. A range is described in terms of starting and ending values for the independent variable that is to be used in the PLOT of LOG.

- RSEQ - REVISE TEST SEQUENCE - NOUN

  This command is used to correct erroneous run descriptions in the test sequence. Corrections are made by entering the sequence number of the bad run description along with the new wave and run I.D. for the sequence entry.

o RUN - EXECUTE RUN SEQUENCE - VERB

This command activates the run processor. The next sequential run/wave combinations are selected from the Sequence Table in the Run Time File and the run and wave names are displayed for operator verification. Acceptance causes the run process to begin.

o SAVE - SAVE TEST COMMANDS - NOUN

This command causes the command lines which have been input since the beginning of the test to be saved in a file followed by an ENDT command. They may be used in an automatic test at a later time.

o SCAN - SCAN SEQUENCE - NOUN

This command is used to specify the number of channels being scanned, the order of scan, and the scan rate for an acquisition system.

o SEAA - SEAKEEPING TEST ANALYSIS - VERB

The SEAA command invokes the Seakeeping test analysis supervisor, which computes the various model parameters, averages, spectra, phases, and RAOs indicated by the analysis mode (regular wave or irregular wave) and the time histories available. The results are stored pending their subsequent use by the Seakeeping output supervisor (SEAO).

- SEAO - SEAKEEPING TEST OUTPUT - VERB

  The SEAO command invokes the SEAO supervisor, which issues the Seakeeping test report quality plots and tabular logs on the Versatec line printer.

- SEQ - TEST SEQUENCE DEFINITION - NOUN

  This command is used to define a sequence of runs by specifying their wave and run definitions. The wave and run definitions are referenced by the names with which they were associated by the WAVE and DRUN commands.

- SFZ - SET FRAME SIZE - NOUN

  This command allows the operator to set the size of the data frames which are used in spectral analysis operations. The frame size, N, must be a power of two in the range ($8 \leq N \leq 4096$). The initial frame size set by the system at the beginning of a test is 2048.

- SHPA - SHP TEST ANALYSIS -VERB

  The SHPA command invokes the SHP analysis supervisor, which computes the various model parameters, averages, spectra, phases, and RAOs indicated by the analysis mode (still water, regular wave, or irregular wave) and the time histories available. The results are stored pending their subsequent use by the SHP output supervisor (SHPO).

o SHPO - SHP TEST OUTPUT - VERB

Ths SHPO command invokes the SHPO supervisor, which issues the SHP test report quality plots and tabular logs on the Versatec line printer.

o STA - COMPUTE STATISTICS - VERB

The STA command processor computes various statistics of the data in a time series or power spectral density file. The statistics are printed on the user's terminal device. The items computed are

1. average,
2. average of the highest third of the data,
3. average of the highest tenth of the data,
4. mean square,
5. root mean square, and
6. standard deviation.

o SUSP - SUSPEND TEST - VERB

This command allows a test to be suspended before it has been completed. The test may then be restarted at a later time.

o SWRD - SELECT WORD PATTERN DEFINITION -NOUN

This command allows select word patterns to be specified for either DMA 1 or 3 of an acquisition system. The pattern is described by specifying which words are desired from the data frame. Words may be specified individually, or a starting location in the frame may be specified along with a repeat count which indicates that the starting location as well as every nth word after that should be retained.

- TANK - TANK IDENTIFICATION - NOUN

  This command is used to identify the tank which will be used for a test. Some other particulars about the tank are also specified by this command.

- TAPE - CREATE TAPE FILE - VERB

  This command is used to save files on magnetic tape.

- TRA - TRANSFER FUNCTION -VERB

  The TRA command processor computes the transfer function relating the two input time series. If a range of frames is specified, the result will be the average of the transfer functions computed from each pair of input data frames. The frame size, N, used in the operation is the spectral analysis frame size in force at the time the command is invoked. The output of the TRA processor is a spectrum consisting of N/2 complex frequency estimates in real-imaginary form.

- TRUN - TRUNCATE TIME HISTORY DATA -VERB

  Via the TRUN command, the operator may remove from the input time series the spurious data which is obtained at the beginning and/or end of a run.

- WAIT - WAIT TIME BETWEEN RUNS - NOUN

  The time period between runs is defined by this command. This wait time is provided to allow for the waves in the tank to subside before the next run.

o WAVE - DEFINE A WAVE - NOUN

This command associates a set of wave characteristics with a name. Ths name is then used in a SEQ command to indicate those characteristics are desired.

o WCAL - ENTER WAVE CALIBRATION MODE - VERB

This command allows the user to enter wave calibration mode, at which time he will be communicating with the 11/05.

o XFER - TRANSFER FILE FROM 11/05 to 11/50 - VERB

This command transfers a file from the 11/05 to the 11/50 and places it under UIC of the user, with the same name that it has on the 11/05.

DUAL FLAP WAVEMAKER

PHASING AND MOTION APPORTIONMENT

BY LINEAR REGRESSION

by

Allen Clark
Marvin Menken

MTS Systems Corporation

1. Introduction

One of the most important considerations in the design of a towing tank facility is its wave generation systems. Usually the desired wave length bandwidth is greater than the well formed range of single degree of freedom wavemakers. One solution to increase the well formed wave band width is to utilize multi-degree of freedom wave-makers. It is the purpose of this paper to apply linear regression to dual flap wavemakers to predict phasing and division of motion between the flaps for well formed waves.

2. Background

Over the years many types of wavemakers have been proposed and used. The more commonly known of these types are the flap, piston, plunger and combination flap and piston. The most common drives for these machines are electro mechanical eccentric and servo hydraulic. The configurations are shown schematically in Figure 1.

The single degree of freedom flap or piston makes well formed waves for only a small wavelength bandwidth, while the plunger suffers from a nonlinear transfer function. Design rules for these machines derive largely from Biesel, et. al. (1951) and later Gilbert, et. al. (1971). They applied classical linear wave theory, as formulated by Havelock (1929) to the wavemaker problem.

Most classical flap and piston wavemakers extend to the bottom of the wave channel. To save wavemaker power requirements and improve the quality of deep water waves, researchers turned to flap wavemakers with depths different from that of the channel. Hyun (1976) extended the work of Biesel for single degree of freedom flap wavemakers with varying depths.

To extend the well formed wave bandwidth, combination flap and piston wavemakers have been designed, e.g. the wavemakers at the wind-wave flume of the Delft Hydraulics Laboratory group (1968). Another technique reported by Hansen and Svendsen (1974) removed some wave distortion by the addition of a non sinusoidal program for a piston wavemaker.

Compton (1970) proposed a segmented two degree of freedom flap generator for the U. S. Naval Academy High Performance Towing Tank. This was to give a wide bandwidth, 2 feet to 100 feet in a wave channel of 16 foot depth, while giving primary emphasis to deep water seakeeping waves. Design of a wave generator along these lines was done by Schneider, et. al. of Kempf and Remmers (1971).

The primary idea of wavemaker design is to match the sinusoidal motion of the waveboard to the natural wave's orbital velocity envelope as much as possible, Figure 2, McCormick (1973). Single degree of freedom wavemakers have a unique wave length that is the most well formed. For waves much shorter than this, energy is imparted into the water below the natural envelope, causing distortion and transverse resonances. For waves longer than the design length, harmonic distortion with a "double humping" harmonic is often seen.

3. Linear Regression Analysis

Intuitively, a segmented flap, like that proposed for the U. S. Naval Academy Hydro mechanics Laboratory, would give a wider wave bandwidth. However, once primary considerations have chosen the hinge depths, how should one predict the proper phasing and flap motion division to give the best design strokes for the wave lengths desired?

Dalzell (1974) formulated the problem based on linear wave theory, and derived a figure of merit which gave design information on the choice of hinge position. From his formulation, he decided practical optimum ratios for the desired wave lengths with the flaps in phase.

These authors took a different approach which has given good experimental results in improving wave distortion and widening the wave generator's bandwidth. It seemed reasonable to use the degrees of freedom of the waveboard to minimize the difference between the waveboard boundary and the natural orbital velocity for the desired wave. A number of different mathematical techniques could be employed for this. For example, equalization of the negative and positive error areas between the segmented board and the natural envelope. However, the simplest and easiest to apply is classical linear regression.

The geometrical mathematical model for this analysis is shown in Figure 3. Since the maximum practical angular strokes are about $\pm$ 10 to 20 degrees, the assumption of small angles is justified.

Using this assumption, the position of the waveboard, $\hat{Y}(X)$, as a function of depth, X, is given by:

$$\hat{Y}(X) = (L - X)\,\Theta + (L-R-X)\,\phi \quad \text{for } 0 \le X \le L-R,$$

$$\hat{Y}(X) = (L - X)\,\Theta \quad \text{for } L-R \le X \le L,$$

and $$\hat{Y}(X) = 0 \quad \text{for } L \le X \le L+F$$

where the symbols are defined by Figure 3.

The squared error from the linear wave envelope function (given in Figure 2.) can now be formed, assuming some discrete interval, Δ, of depth, X.

$$E_{\Delta}^{2}(\theta, \phi) = \sum_{i=0}^{N=\frac{L}{\Delta}} \left(Y(X_i) - \hat{Y}(X_i) \right)^2$$

$$E_{\Delta}^{2}(\theta, \phi) = \sum_{i=0}^{\frac{L-R}{\Delta}} \left(Y(X_i) - \{L - X_i\}\theta - \{L-R-X_i\}\phi \right)^2$$

$$+ \sum_{i=\frac{L-R}{\Delta}+1}^{\frac{L}{\Delta}} \left(Y(X_i) - \{L - X_i\}\theta \right)^2 + \sum_{i=\frac{L}{\Delta}+1}^{\frac{L+F}{\Delta}} Y^2(X_i)$$

Maintaining generality for wavelengths of interest, we minimize this error function by taking partial derivatives and setting them equal to zero:

$$\frac{\partial E^2}{\partial \theta} = 2\sum_{i=0}^{\frac{L-R}{\Delta}} \left(Y(X_i) - \{L-X_i\}\theta - \{L - R - X_i\}\phi \right) \{X_i - L\}$$

$$+ 2\sum_{i=\frac{L-R}{\Delta}+1}^{\frac{L}{\Delta}} \left(Y(X_i) - \{L-X_i\}\theta \right) \{X_i - L\} = 0 .$$

$$\frac{\partial E^2}{\partial \phi} = 2\sum_{i=0}^{\frac{L-R}{\Delta}} \left(Y(X_i) - \{L-X_i\}\theta - \{L-R-X_i\}\phi \right) \{X_i + R - L\} = 0 .$$

Choosing a particular wave for Y(X), performing the indicated summations, and setting the error derivatives equal to zero yields two linear equations in two unknowns for the required optimum θ and ϕ :

$$A\,\theta + B\,\phi = C$$
$$D\,\theta + E\,\phi = F$$

where A, B, C, D, E and F are constants from the summations for a particular wave length. It has been assumed that θ and ϕ are sinusoidal with the same frequency as the desired wave.

These equations are easily programmed for automatic solution on a digital computer over the range of wavelengths of interest.

4. Results

A summary plot of the application of this technique is given in Figure 4 for the case of the wave generator for the 380 foot towing tank at the U. S. Naval Academy. The wavelength range of interest is from 2 to 100 feet with a tank depth of 16 feet. The dual flap hinge positions are shown on the figure. Several interesting and intuitively appealing results can be noted.

First, there is a distinct wavelength where only the top flap is used, 9 feet. At a wavelength of 35 feet both top and bottom flaps are moved as a single rigid unit. For wavelengths less than 9 feet, the bottom flap is predicted to move backward, and the top flap provides most of the motion. For wavelengths greater than 35 feet, the top flap backs up and is held nearly vertical while the bottom flap moves forward. In these regions the flaps are programmed out of phase. An example of this type of motion is shown exaggerated in Figure 5. for the U. S. Naval Academy 120 foot tank dual flap wavemaker.

In between, the two single flap operation points, the results require the flaps to move in phase, with varying proportions as wavelength is increased.

Wavemakers designed by use of the theory have been shown by experiment to have increased well formed wave length bandwidths. For the shorter wave lengths, the tendency to transverse oscillations has been decreased and the "double humping" harmonic on the longer wavelengths can be removed by use of out of phase motions.

Figure 6 and Table 1 compare experimental lowest distortion phasing and apportionment with the theoretical values predicted by the technique.

5. Further Work

The technique can be extended to general multi-degree of freedom waveboards. This could be achieved by formulating more least squares error equations for the additional unknown variables.

By iterative use, the technique could be used for selecting optimum hinge positions.

Finally, more detailed theortical analysis could be performed by applying higher order wave theories for the wave orbital velocity function.

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FIGURE 1.

WAVEMAKER DESIGNS

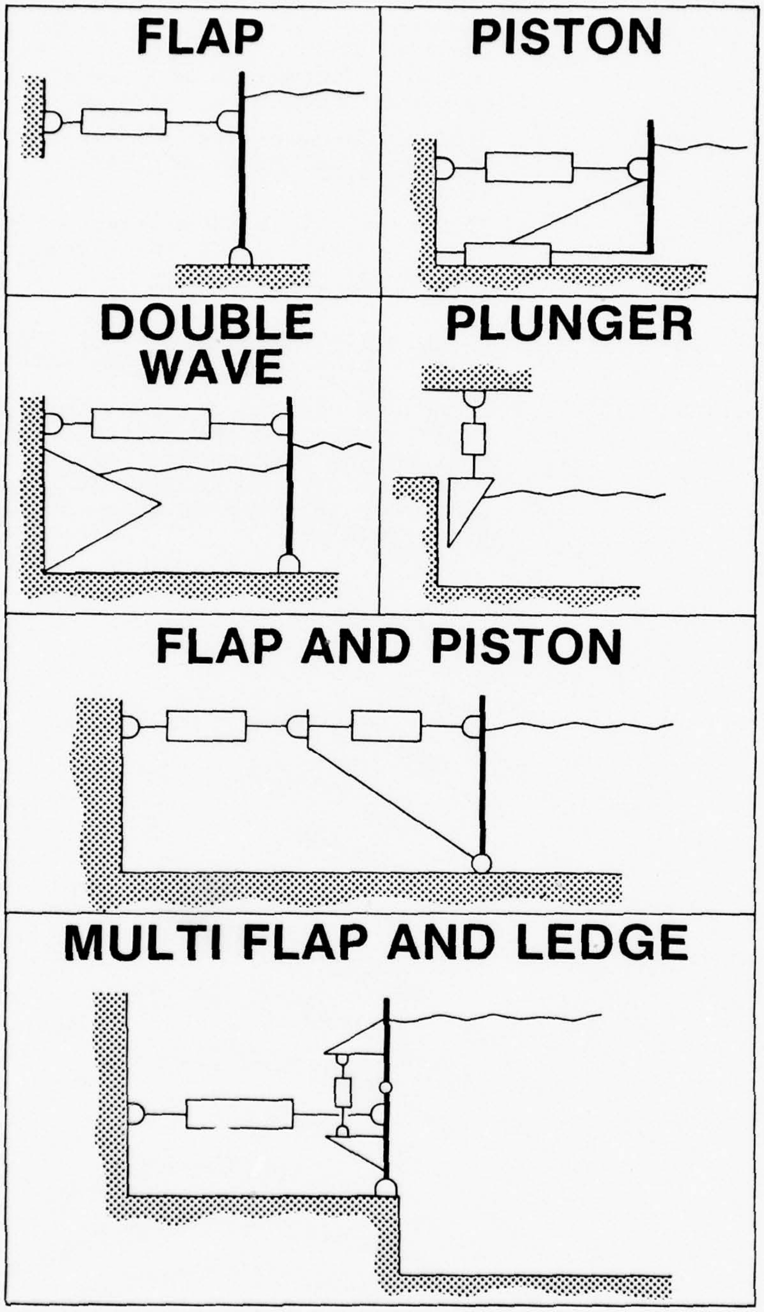
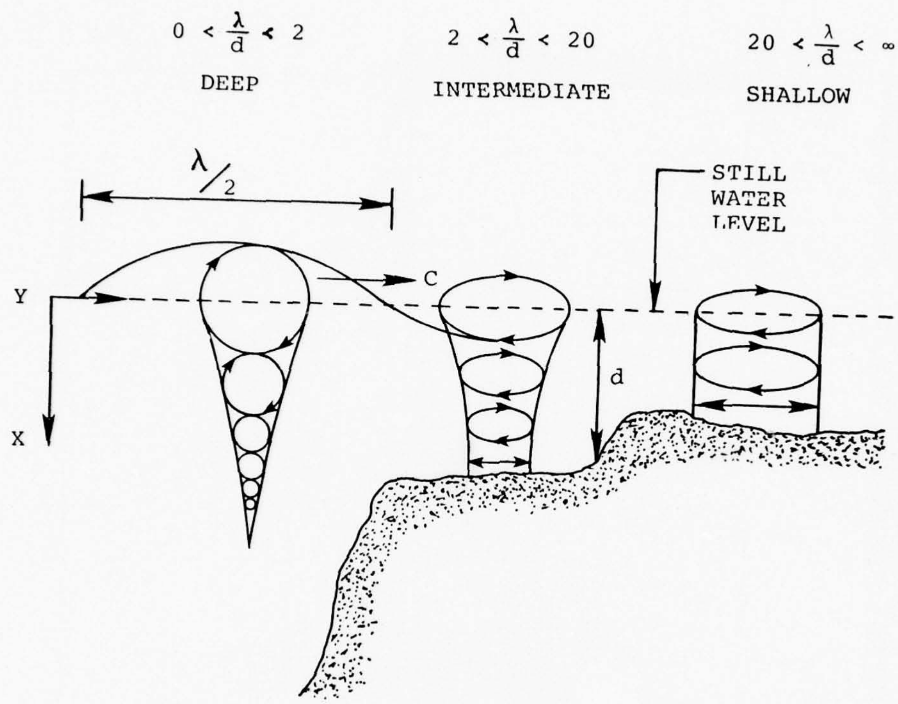


FIGURE 2.

WAVE ORBITAL VELOCITY ENVELOPES



$$y(x) = \frac{H}{2} \frac{\cosh \frac{2\pi}{\lambda}(d - x)}{\sinh \frac{2\pi d}{\lambda}}$$

For $\frac{\lambda}{d} < 2$, $y(x) \approx \frac{H}{2} e^{\frac{-2\pi}{\lambda} x}$

$$\omega^2 = \frac{2\pi g}{\lambda} \tanh \frac{2\pi d}{\lambda}$$

FIGURE 3

GEOMETRICAL MATHEMATICAL MODEL

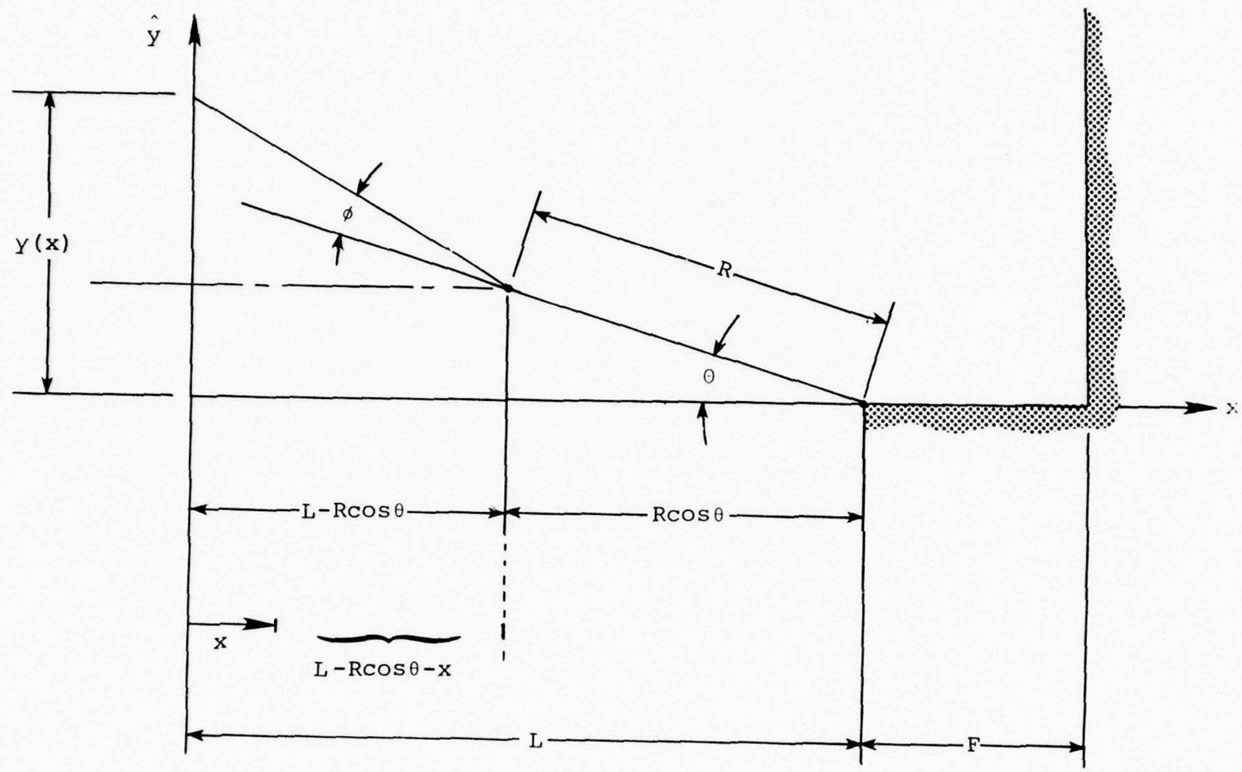


FIGURE 4.

LINEAR REGRESSION DUAL FLAP PHASE AND MOTION APPORTIONMENT U.S. NAVAL ACADEMY 380 FOOT TANK

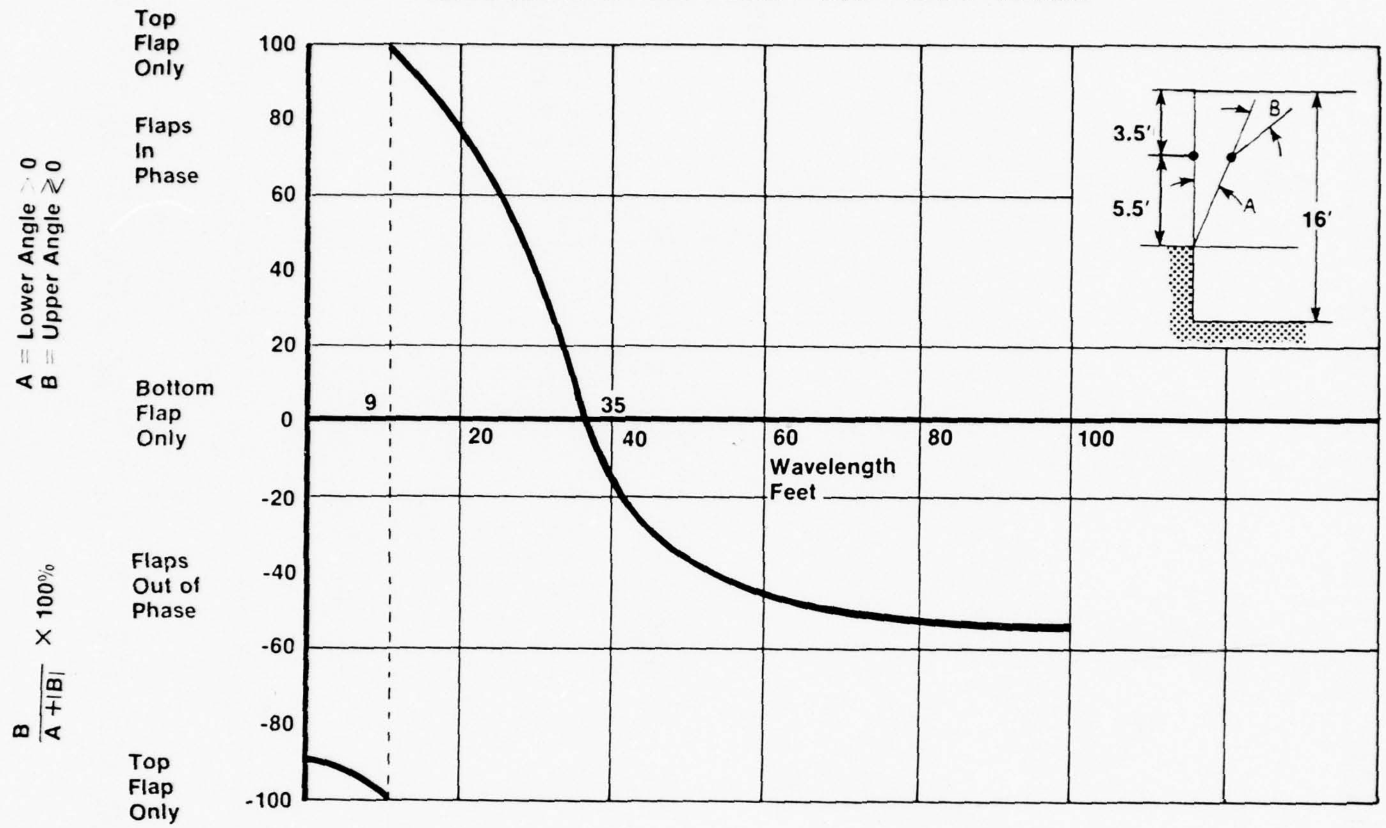
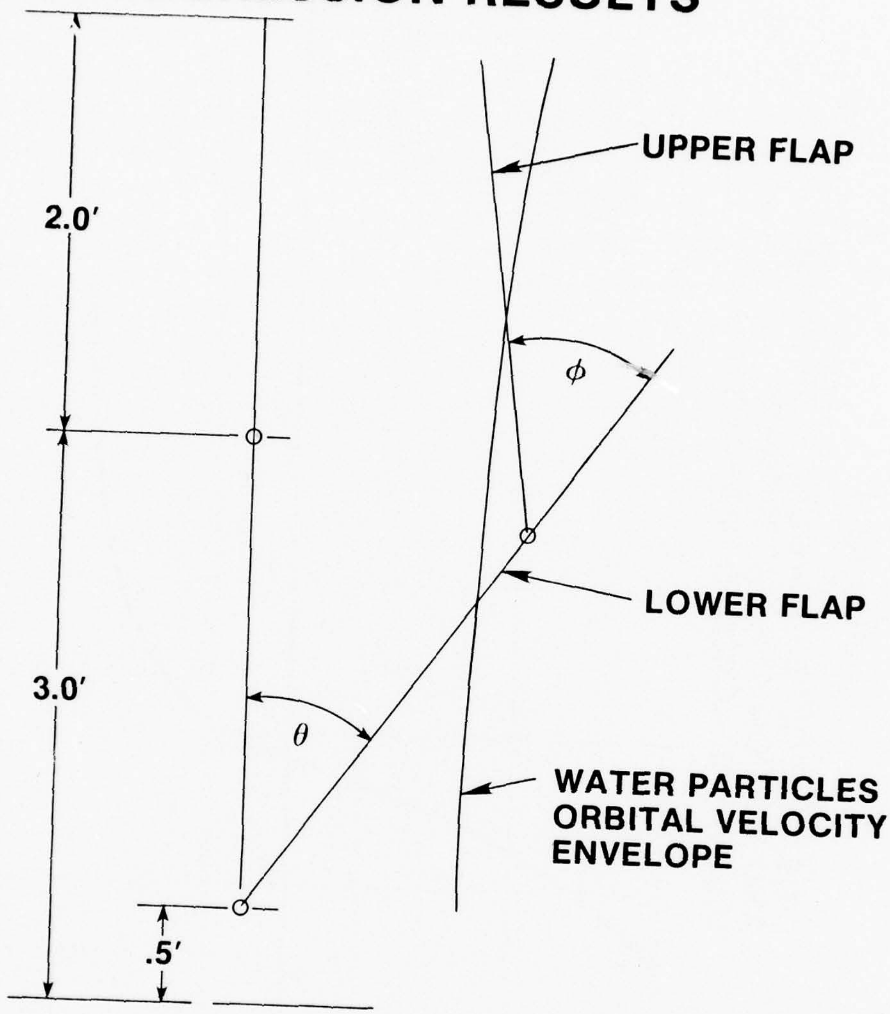


FIGURE 5.

EXAMPLE WAVELENGTH DUAL FLAP LINEAR REGRESSION RESULTS



$\frac{\phi}{\theta} = -1.2$ $\lambda = 40$ FEET $\frac{\lambda}{d} = 8.0$

USNA 120 FT. TANK TWO FLAP WAVEMAKER

FIGURE 6.

EXPERIMENTAL RESULTS — LINEAR REGRESSION PHASING AND APPORTIONMENT

Linear Regression

Flap Control

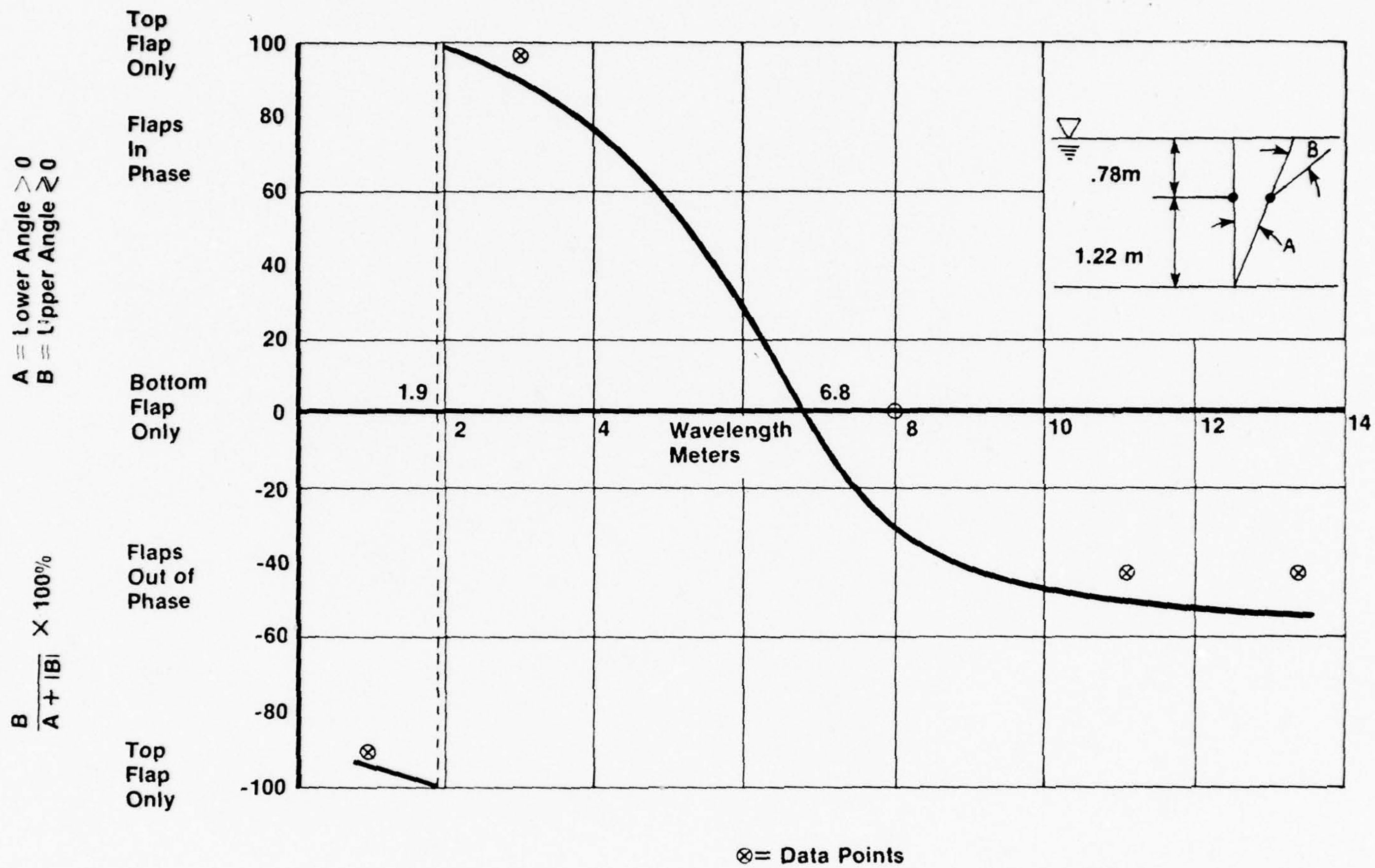


Table 1

Harmonic Distortion Compared Between

A Single Flap and Double Flap Wave Generator

Water Depth = 2 meters

Wave Length (m)	Harmonic Distortion (%)	
	Single Flap	Optimum Double Flap Ratio
.9	10.9	5.6
3.0	10.1	5.0
8.0	3.5	3.5
11.0	15.3	10.3
13.4	11.8	3.7

An Algorithm for Predicting Breaking

Waves in a Towing Tank

Charles H. Anderson MTS Systems Corporation
Bruce Johnson U.S. Naval Academy

One problem associated with the generation of irregular waves for ship model tests in a towing tank is the appearance of breaking waves somewhere in the wave train. This results in a redistribution of spectral energy in the generated wave spectrum and causes the wave energy to be non-stationary (time varying) in terms of spatial distribution in the tank. Many tanks avoid this by using only low sea states for irregular wave tests or just quietly hope the problem won't be noticed for larger sea states.

The advent of computer generated irregular waves raises the possibility of trying to predict whether or not breaking waves will occur in a specific wave generator drive signal. Although wave steepness (wave height/wave length) is difficult to define in irregular waves, wave slope can be derived from a wave record which consists of a sum of sinusoids with or without random phase. (For regular waves the ration of maximum wave slope to "wave steepness" is equal to π. Reference (1) (Lewis). This randomized sum of sinusoids technique is described in reference (2) (Anderson-Johnson) and involves the knowledge of the wavemaker transfer function (amplitude and phase) and an analytical description of the proposed drive signal.

A wave breaking predictor is attractive in that a proposed drive signal can be tested for the possibility of breaking waves without having to generate the actual waves in the tank once an experimentally determined maximum wave slope has been established. This greatly reduces the calibration time required for a new wave spectrum specified for a given test.

One of the key items in the predictor is the transfer function between the waveboard drive signal and a response signal from a wave height transducer in the tank. This is a measurement of the system response Z to an input, X, as a function of frequency, commonly denoted H (see figure 1).

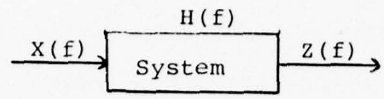


Figure 1

The transfer function H(f) is commonly measured using a random or under certain conditions a periodic random drive signal. The technique for measuring H(f) and the coherence function γ^2 (f) using a random signal has been outlined by Otnes and Enochson (3). In a random drive signal the phase angles of each frequency component are rerandomized for each new frame. Thus if a wave probe is located such that the time for the longest wavelength to travel from the probe to the beach and back is greater than the time to output a frame of the drive signal, a random phase relationship will exist between the respective components of the progressive and reflected waves at the probe. This allows the beach reflection to be treated as extraneous noise. If the reflected component is in phase for a small portion of the sampled frame, the reflection may still be treated as random since in a majority of the frame, the phases have a random relationship.

One problem that may occur in transfer function measurement in a wave tank is that the time for the shorter waves to travel from the board to the wave probe may be greater than the time to output a frame. Thus the random phase relationship will exist between the drive and waveheight signals at a particular instant in time and the transfer function cannot be measured. A solution to this problem involves using a periodic random drive signal. The number of periodic frames selected should be such that the shortest waves are present at the probe for an entire frame, but the longest waves have not had time to reflect back to the probe for more than a small part of the frame. The only drive and response signals analyzed are then the last periodic frame of the drive signal and its corresponding response frame for each phase rerandomization. The transfer function is calculated from these frames using the technique referenced above.

Using the measured transfer function, it is possible to predict the response (waveheight signal) to a given drive signal using the following formula (written in the frequency domain)

$$Z(f) = H(f)X(f) \tag{1}$$

or written in the time domain

$$\zeta\ (t_k) = \sum_{m=o}^{N} X(t_m) \quad h\ (t_k - t_m) \tag{2}$$

Where

$$h(t_k) = \Delta f \sum_{m=o}^{N/z} H(f_m)e^{j2\pi f_m t_k} \qquad j = (-1)^{1/2} \tag{3}$$

Using linear wave theory, the formula for a 'right running' progressive wave is

$$\zeta(x,t) = \sum_{k=1}^{N/2} \frac{H_k}{2} \cos 2\pi \left(\frac{x}{L_k} - f_k t + \phi_k\right) \tag{4}$$

The slope of this wave is

$$\frac{\partial\zeta}{\partial x}(x,t) = -\sum_{k=1}^{N/2} \frac{H_k \pi}{L_k} \sin 2\pi \left(\frac{x}{L_k} - f_k t + \phi_k\right) \tag{5}$$

For a regular wave (single frequency) this will have a peak value of $\pi \frac{H}{L}$.

Thus given the wave signal at the wave probe, we can compute the wave slope also. To calculate the slope at any other point in the tank, we need only determine the wave signal at that point. By replacing x in equation (4) with $x + \Delta x$ we find that the wave-height signal at a distance Δx from the probe is

$$\zeta(x + \Delta x,\ t) = \sum_{k=1}^{N/2} \frac{H_k}{2} \cos 2\pi\left(\frac{x + \Delta x}{L_k} + f_k t + \phi_k\right) \tag{6}$$

Because we ultimately wish to predict the wave slope at any point in the tank, and because the transfer function is expressed in the frequency domain, it would be convenient to express the relationships between equations (4) and (5) and equations (4) and (6) in the frequency domain also. Taking the Fourier transform of equations (4) and (5) gives us respectively

$$Z(x,\ f_k) = F\left[\zeta(x,\ t)\right] = \frac{H_k}{4} \cos 2\pi\left(\frac{x}{L_k} + \phi_k\right) \tag{7}$$
$$- j \sin 2\pi\left(\frac{x}{L_k} + \phi_k\right)\Big]$$

$$\frac{\partial Z(x, f_k)}{\partial x} = F\left[\frac{\partial \zeta (x,t)}{x}\right] = \frac{\pi H_k}{2L_k}\left[- \sin 2\pi \left(\frac{x}{L_k} + \phi_k\right) - j \cos 2\pi \left(\frac{x}{L_k} + \phi_k\right)\right] \quad (8)$$

Note that

$$\frac{\partial Z(x,f_k)}{\partial x} = -j \frac{2\pi}{L_k} Z(x,f_k) \quad (9)$$

This gives us a frequency domain relationship between waveheight and wave slope.

The Fourier transform of equation (6) is

$$Z(x + \Delta x, f_k) = \frac{H_k}{4}\left[\cos 2\pi \left(\frac{x + \Delta x}{L_k} + \phi_k\right) - j\sin 2\pi \left(\frac{x + \Delta x}{L_k} + \phi_k\right)\right]$$

$$= Z(x,k) * \left[\cos \frac{2\pi\Delta x}{L_k} - j \sin \frac{2\pi\Delta x}{L_k}\right]$$

$$= Z(x,k) * e^{-j\frac{2\pi\Delta X}{L_k}} \quad (10)$$

Thus the frequency domain relationship between the wave height at the transducer and the wave slope at any point in the tank is

$$\frac{\partial Z(x + \Delta x, f_k)}{\partial x} = - j \frac{2\pi}{L_k} Z(x, f_k) * e^{-j\frac{2\pi\Delta X}{L_k}} \quad (11)$$

The wave slope at this point as a function of time could then be calculated using the inverse fourier transform.

The technique was tested at the U.S. Naval Academy in the 120 foot tank. This tank has a two flap rotational waveboard with each flap capable of independent motion. (see figure 2)

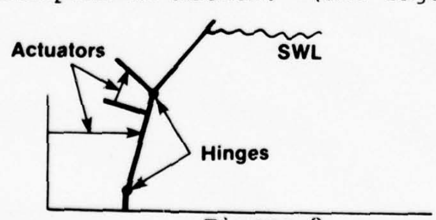
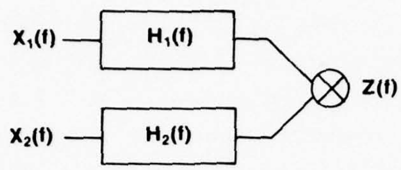


Figure 2

Because this is a two input system (each flap is independent) figure 1 must be modified to reflect the change in our model. The revised model is shown in figure 3.



Equation 1 must be rewritten as

$$Z(f) = H_1(f)X_1(f) + H_2(f)X_2(f) \tag{12}$$

$H_1(f)$ and $H_2(f)$ were measured separately. In both cases a periodic random drive signal was used. See reference (2). This consists of a series of frames of data where every other frame is identical to the previous one, i.e. frames 1 and 2 are identical, frames 3 and 4 are identical, etc. Only the response data corresponding to the second frame of each pair is used to calculate the transfer function. By doing this the response data may be treated as a sum of sine waves rather than as random data. This increases the statistical accuracy of the transfer function measurement over that obtained using purely random drive signals.

The wave probe was located 25 feet from the waveboard so that only the lowest frequencies have time to reflect back to the probe. This also allowed the shortest waves to be at a constant phase relationship with the drive signal for the entire second frame.

Figures 4 and 5 give the magnitude and phase respectively of the transfer function between the lower flap drive signal and the waveheight transducer signal. (The phase plot actually represents a large time delay. Because the phase routine only calculates angles between -180° and 180°, the wrap around makes the phase look random. Figures 6 and 7 give the magnitude and phase respectively of the transfer function between upper flap drive signal and the waveheight transducer signal. The coherence functions for the lower and upper transfer functions are given in figures 8 and 9 respectively. The coherence functions show a high degree of linearity between the drive and waveheight signals. Even at lower frequencies where beach re-

flection can be a problem the coherence is high, indicating the beach is doing an adequate job absorbing the waves. The dip above 1.4 hertz indicates some type of unknown tank resonance.

To test the breaking wave predictor, four periodic drive signals were used. (In a periodic signal, all frames are identical, although they may have many frequency components. It is essentially the sum of sine waves having a common fundamental frequency). Signals 1 and 3 have identical spectral densities. Only the phase angles assigned to each frequency component are different. Similiarly signals 2 and 4 have identical spectra but different phasing. Signals 1 and 2 caused breaking waves while signals 3 and 4 did not. Because the drive signals are periodic, the response signal and therefore the wave slope signal is also periodic in the same interval. Thus the maximum absolute of the slope seen within this period is also the maximum absolute that will be seen while the waveboard is driven with this signal.

A plot was made of the maximum absolute value of the wave slope during the given signal period as a function of distance from the waveboard. These plots for signals 1 thru 4 are given in figures 10 thru 13 respectively. The maximum slopes are noticeably higher for those signals which caused breaking waves than for those which did not. Because the only fact noted at testing time was whether or not the wave broke, it can not be verified that the technique can be used to predict where waves will break.

Wiegel (4) states that for progressive waves, a limiting wave steepness (H/L) of .142 can be used. The maximum slope (multiplying by π) is therefore .446. Since signal 2 has a peak of only about .41, a lower value is probably more realistic for irregular waves: (slope ≤ 0.4, $\frac{H}{L} \leq 0.13$).

The experimental data confirms that this procedure can be used to predict breaking waves for periodic signals. Because the maximum wave slope is proportional to H/L, the wave steepness, for regular waves, the technique is also consistant with regular wave theory.

REFERENCES

1.	Lewis, E.V. (1967)	"The Motion of Ships in Waves", Chapter 9 of Principles of Naval Architecture, J.P. Comstock, edr, SNAME, New York
2.	Anderson, C.H., Johnson, B.	"A Computer Controlled Wave Generator System for the U.S. Naval Academy", Proceedings of the 18th ATTC
3.	Otnes, R.K. Enochson, L.	"Transfer Function and Coherence Function Computations", Chapter 9 of Digital Time Series Analysis, John Wiley & Sons, New York
4.	Wiegel, R.L.	"Limiting Steepness of Progressive Waves", P. 40 of Oceanographical Engineering, Prentice - Hall, Inc. Englewood Cliffs, N.J.

Lower Flap Drive Signal to Waveheight Transfer Function
Amplitude

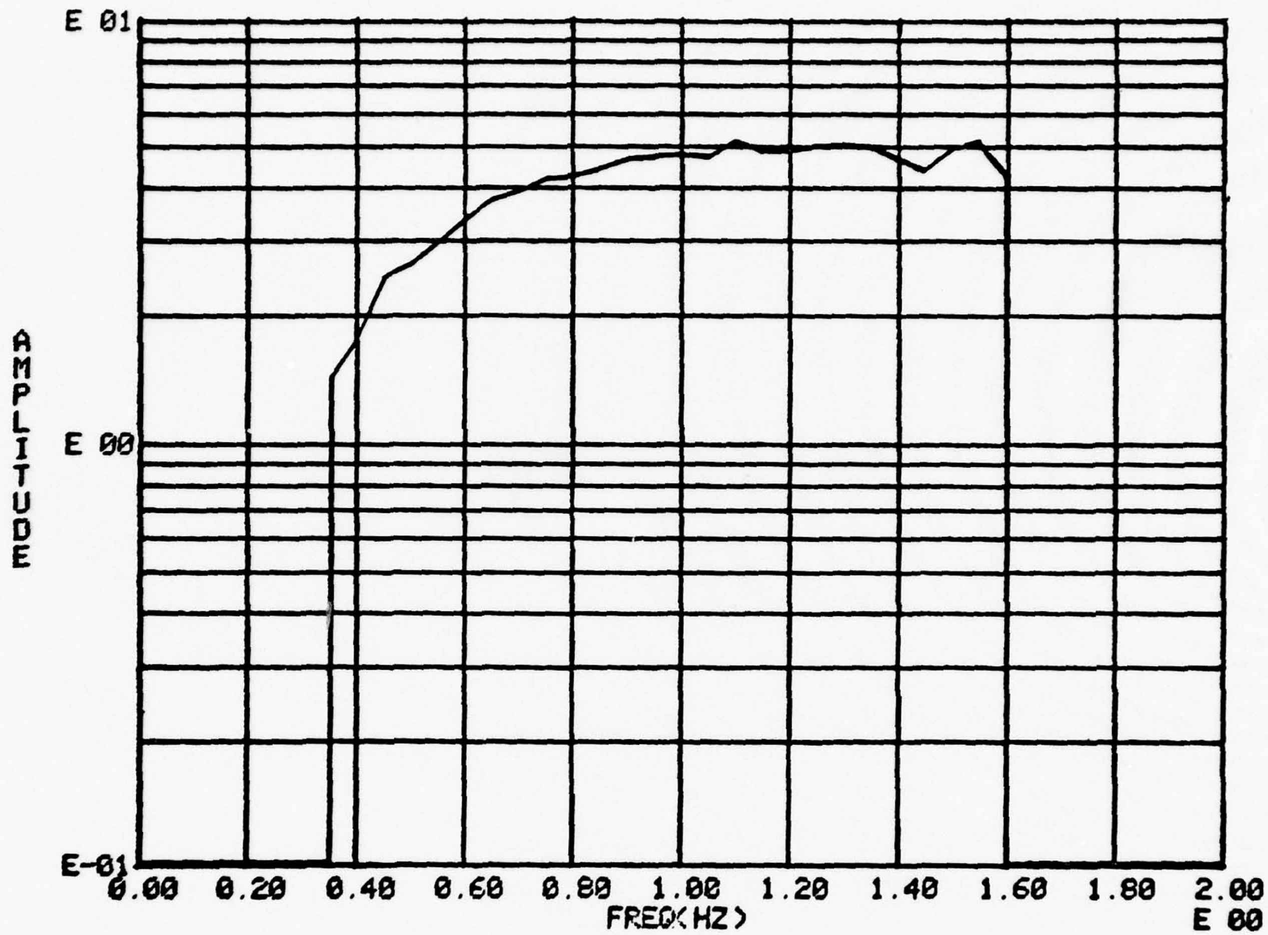


Figure - 4

Lower Flap Drive Signal to Waveheight Transfer Function

Phase

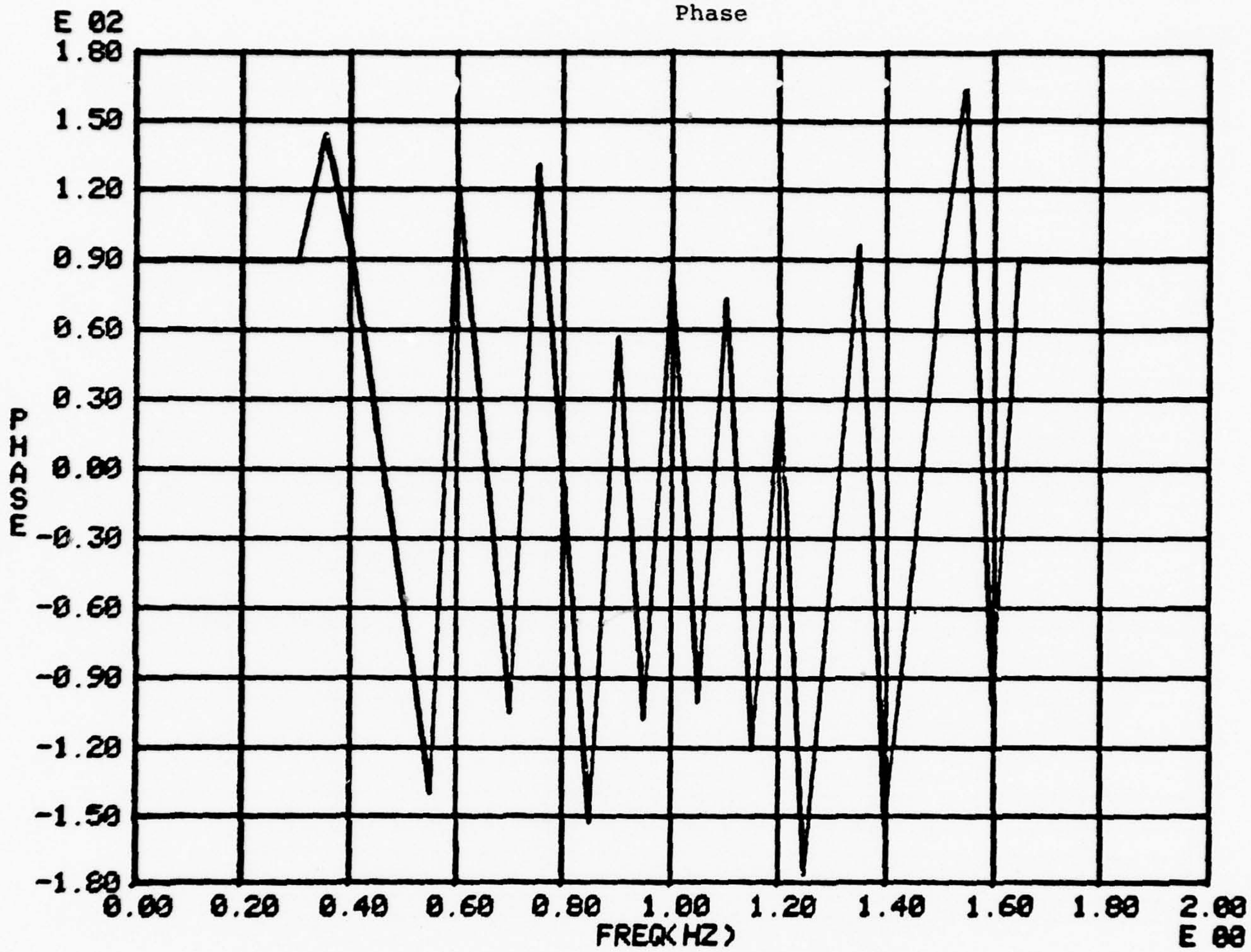


Figure - 5

Upper Flap Drive Signal to Waveheight Transfer Function

Amplitude

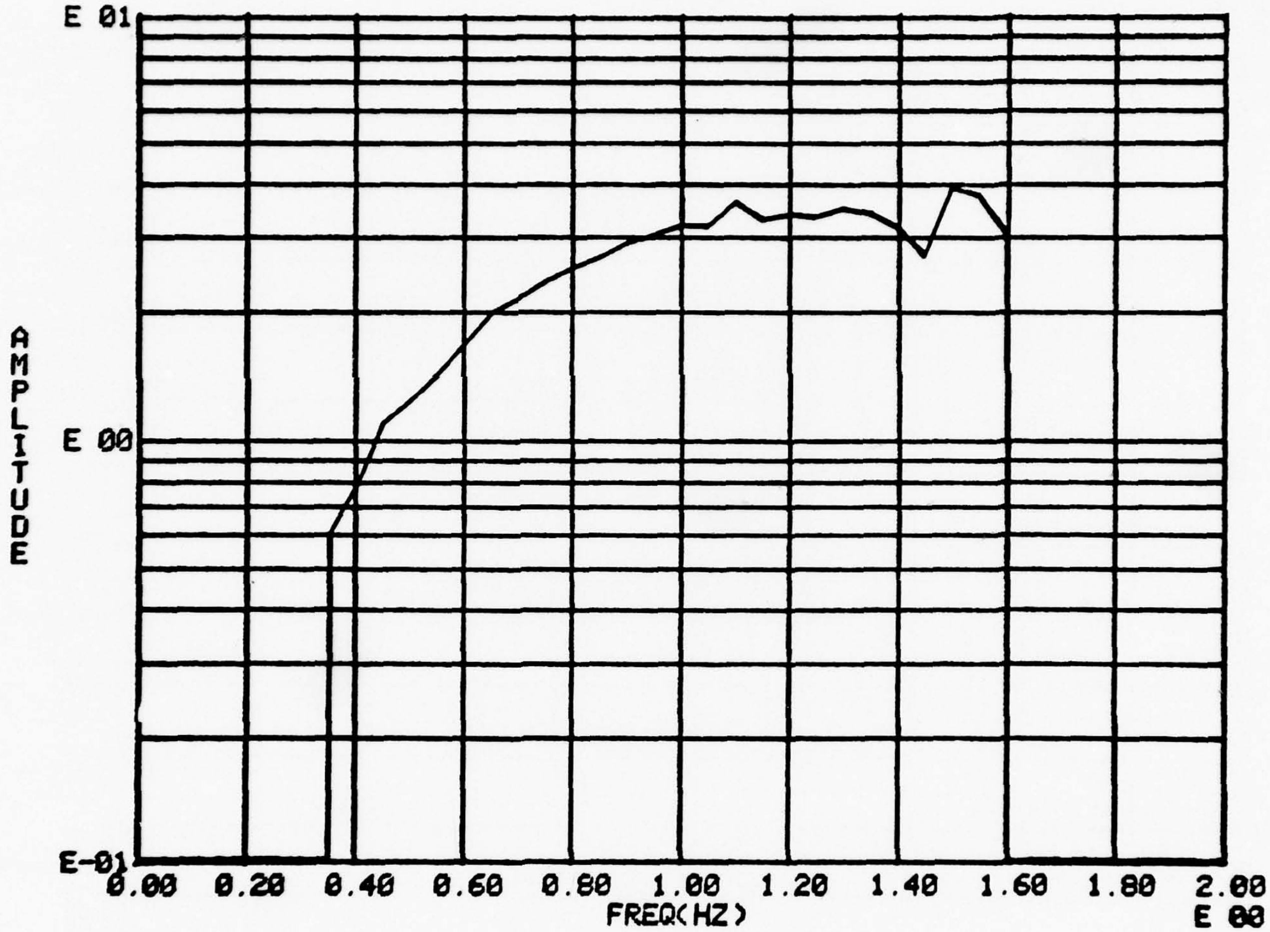


Figure - 6

Upper Flap Drive Signal to Waveheight Transfer Function

Phase

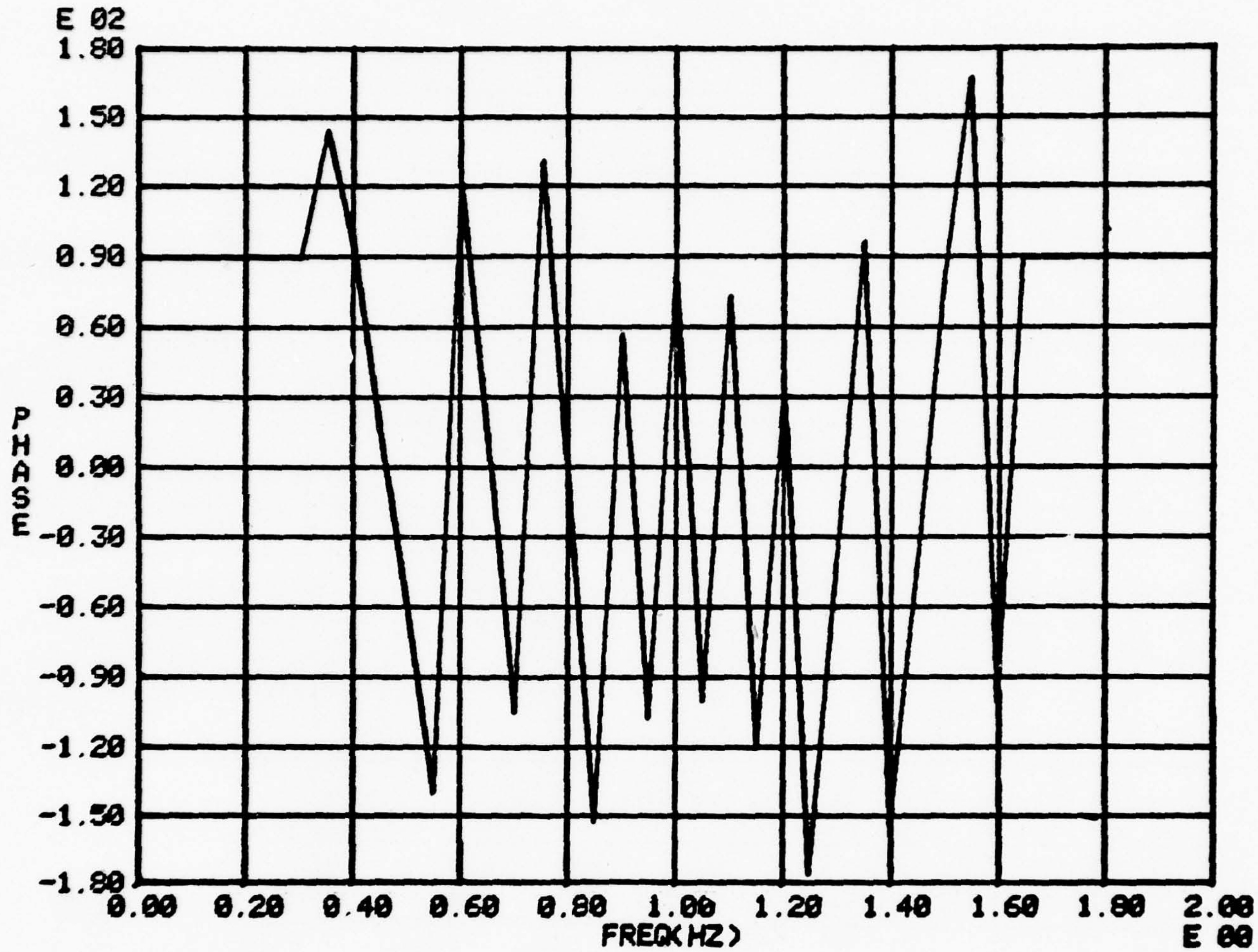


Figure - 7

Lower Flap Drive Signal to Waveheight Coherence

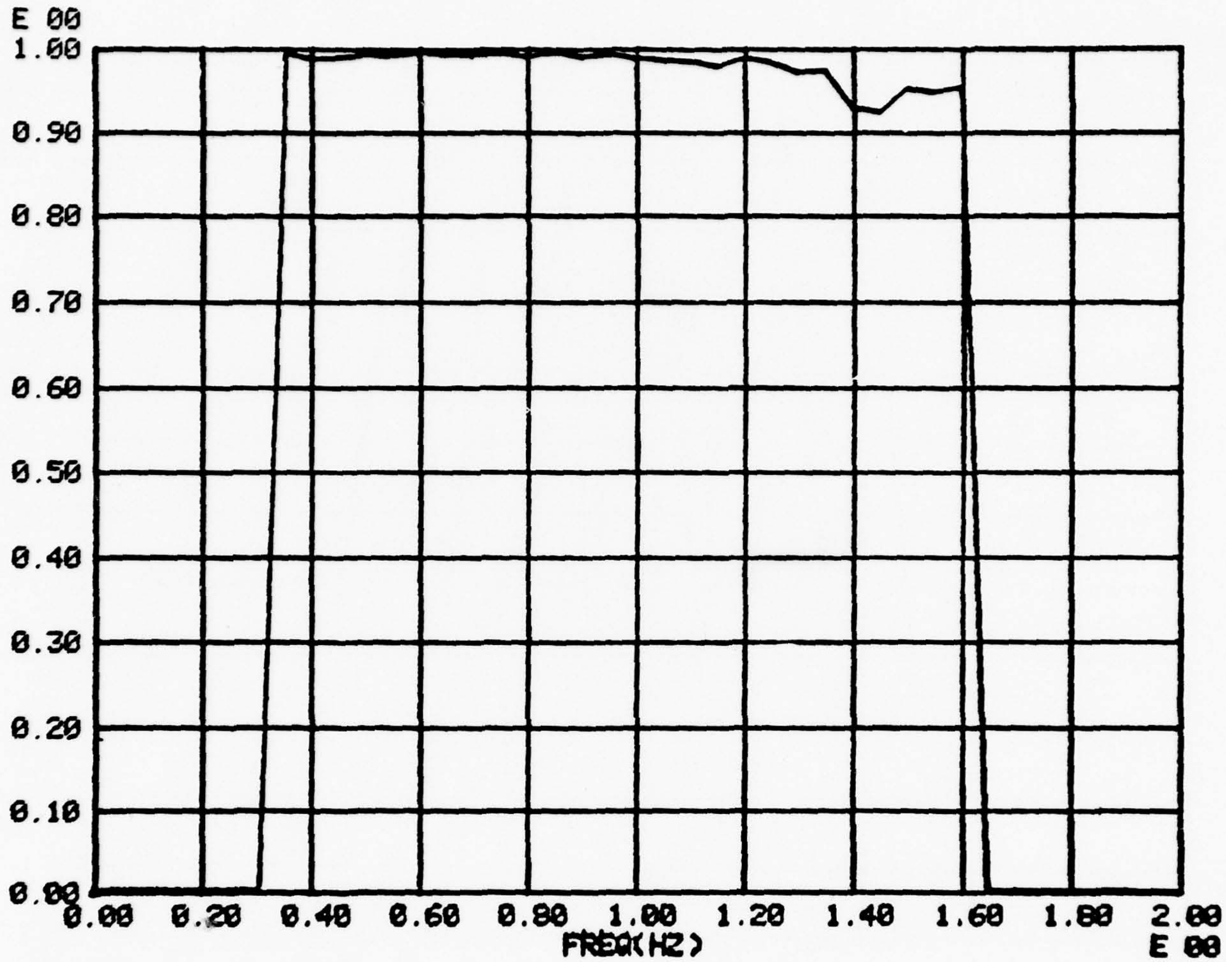


Figure - 8

Upper Flap Drive Signal to Waveheight Coherence

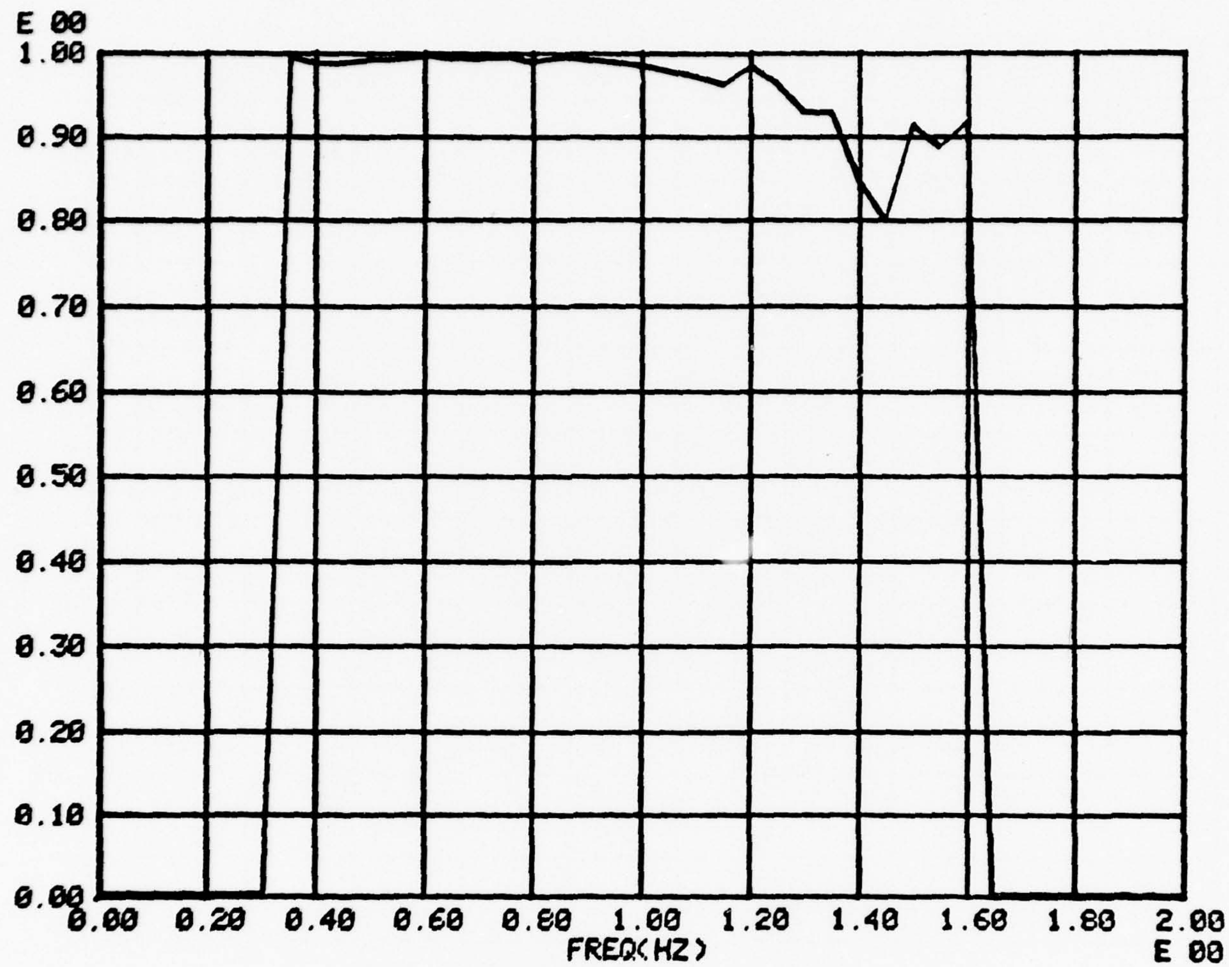


Figure - 9

Predicted Peak Wave Slope for Signal 1

Breaking Waves Produced

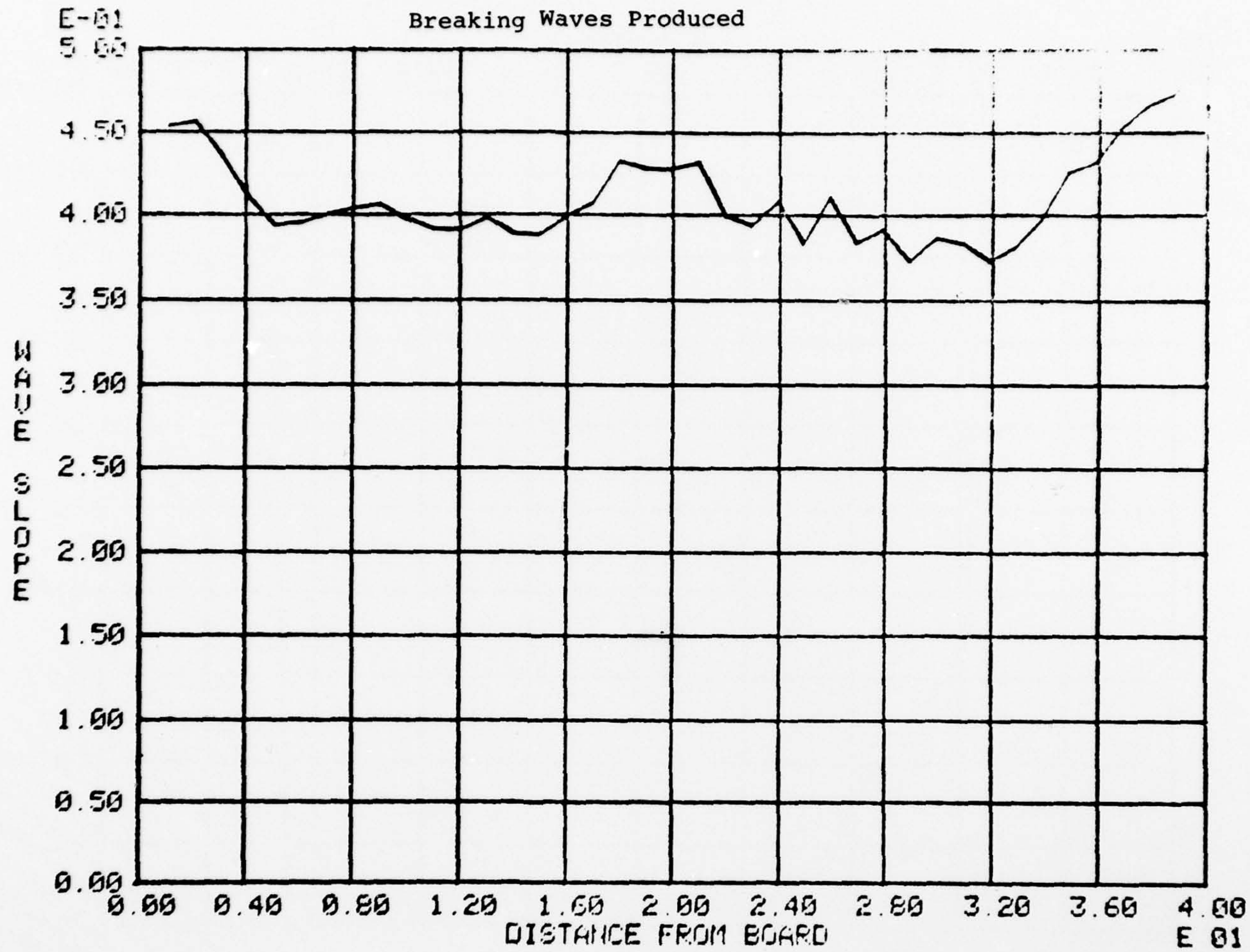


Figure - 10

Predicted Peak Wave Slope for Signal 2

Breaking Waves Produced

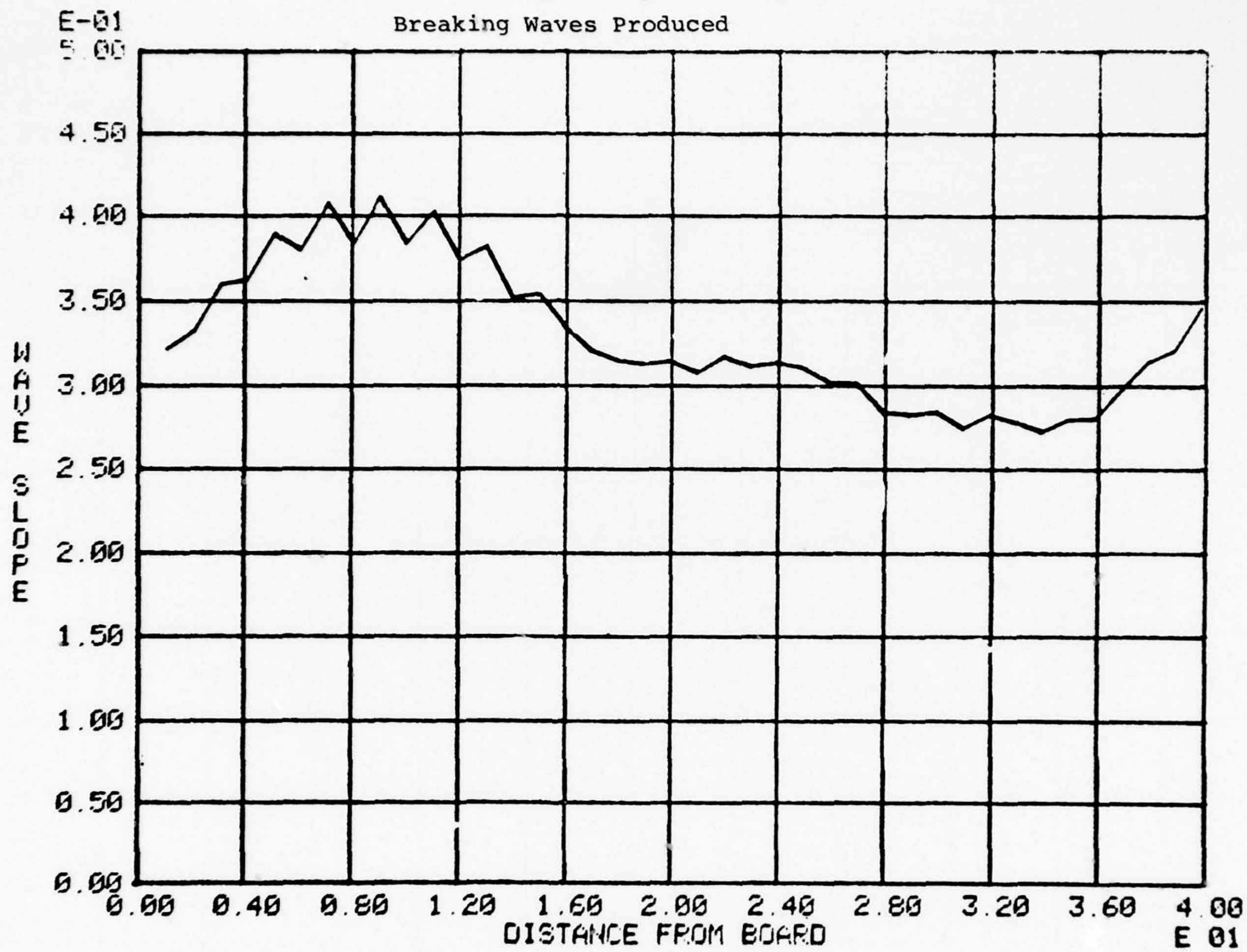


Figure - 11

Predicted Peak Wave Slope for Signal 3

No Breaking Waves

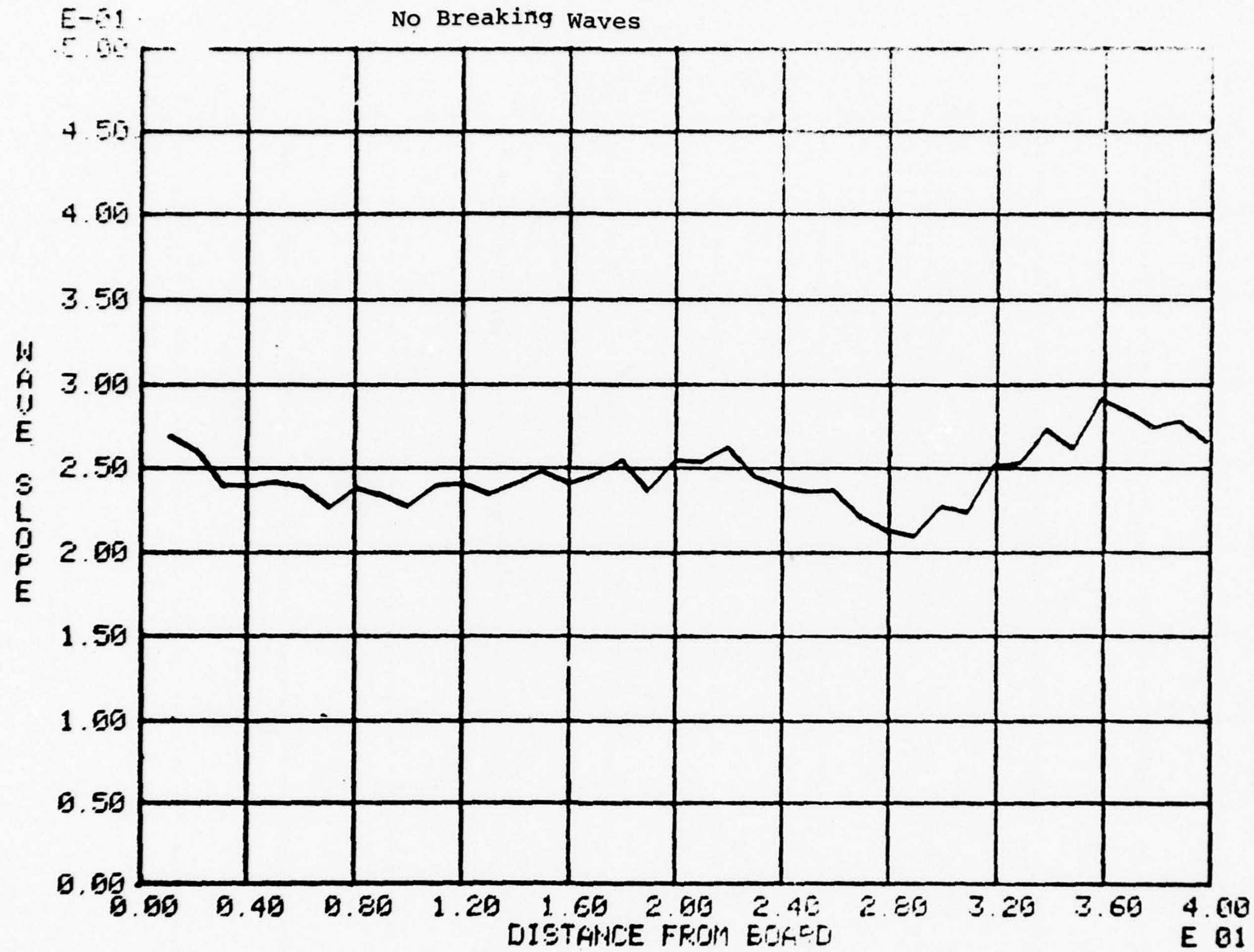


Figure - 12

Predicted Peak Wave Slope for Signal 4

No Breaking Waves

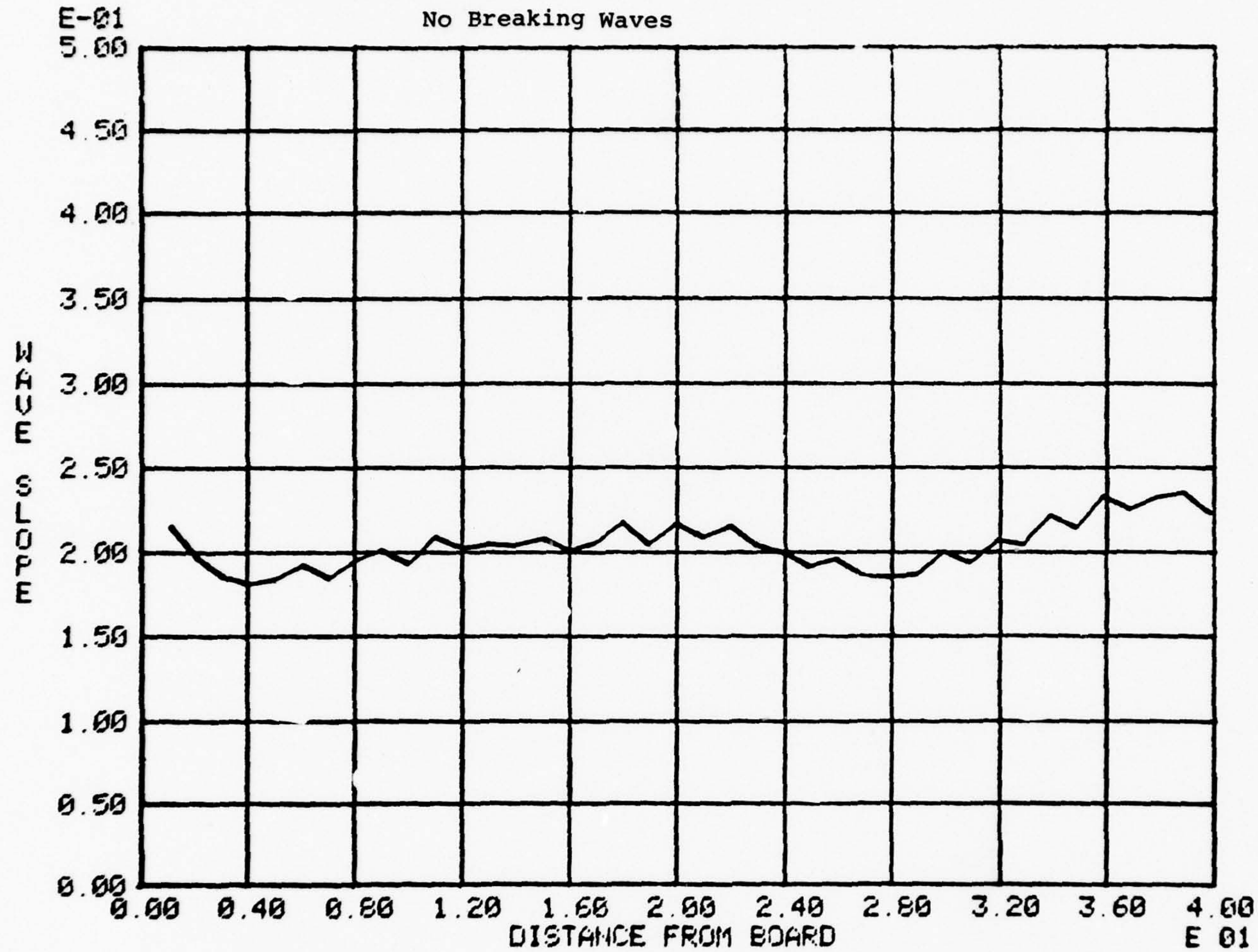


Figure - 13

A COMPUTER CONTROLLED WAVE GENERATION SYSTEM
FOR THE U.S. NAVAL ACADEMY

by

Charles H. Anderson, MTS Systems Corporation
Bruce Johnson, U.S. Naval Academy

The problem of generating a "random" signal of specified spectral content has been attacked in many fields (areas) of test engineering. In some cases, the statistical problems have been resolved through the use of digital techniques and random testing procedures have become quite common. In other areas, such as towing tank testing, however, the use of random waves is limited by several problems. The non-linearity of many wave generators makes it quite difficult to control spectral shape accurately, and statistical reproducibility is adversely affected by breaking waves, beach reflections and the relatively short duration of most tank tests.

A computer controlled wave generation system has been designed and tested at the U.S. Naval Academy Hydromechanics Laboratory which attempts to resolve several of the problems listed above. This system which drives the servo-hydraulic dual-flap wavemakers in the 380' and 120' towing tanks as well as the single flap wavemaker in the Coastal Engineering tank is capable of generating single frequency, multiple frequency, random or pseudo-random waves with a specified spectral content. The system has a demonstrated capability to generate the constant amplitude/constant slope wave spectrum proposed at the 17th ATTC by Johnson (1) and used by Springett, Chen, and Biewer, (2), in tests of offshore platforms. This wave spectrum is defined by

$$G(f) = \begin{cases} \dfrac{H^2}{8\Delta f} & \text{for } f_1 \leq f \leq f_2 \quad \text{(Constant amplitude)} \\ \dfrac{H^2}{8\Delta f}\ \dfrac{f_2^4}{f^4} & \text{for } f_2 \leq f \leq f_{max} \quad \text{(Constant slope)} \\ 0 & \text{elsewhere} \end{cases}$$

The system also allows the operator to define an arbitrary spectrum which may consist of a single frequency component or up to 40 or 50 components depending on the frequency resolution specified by the operator. Once the desired spectrum is defined, the system will drive the wave board, while recording wave height data. By comparing the achieved wave height spectrum to the desired wave height spectrum the system can modify the frequency components of the drive signal to achieve the desired spectrum in the tank to within some specified tolerance limits. The system will iterate on the drive signal components until the desired wave spectrum is achieved. Once a desired spectrum has been achieved, the drive signal which gave that result can be saved as a digital time series and used as often as desired without having to go thru the iteration procedure again.

The computer for the system consists of a PDP 11/05 with an RK11 disk controller and drive and a TA11 dual drive cassette. The cassette is used for loading the system and extra storage while the RK11 is used for all other purposes requiring mass storage. The computer is hooked to an MTS 433 interface consisting of two digital to analog (D/A) convertors each with a 10 hertz, 8 pole, Butterworth filter, one analog to digital (A/D) convertor with a similar filter, and a programmable clock. Filters are used on the digital to analog convertors to provide a smooth, band-limited drive signal to the wave board

controller. The filter on the analog to digital convertor prevents high frequency noise from aliasing down into the analysis range of interest (see figure 1).

The system drives the two flap waveboard with the D/A convertors using a drive signal prepared before hand. It simultaneously samples waveheight data from a wave probe located down tank with the A/D convertor and stores it on the disk.

The computer uses DEC's RT-11 single job operating system with all application programs written in FORTRAN. The application software consists of four major programs (see figure 2). Each program requires a few simple inputs from the operator to determine among other things what data files to use and where to put new data. The programs communicate with each other thru data files stored on the RK11 disk.

The first program (DEFINE) allows the operator to define the spectrum he wants to see in the tank. The user must specify the frame length, T (in seconds), and the number of points per frame N. This allows the program to calculate the resolution bandwidth $\Delta f = 1/T$, output rate $f_s = N\Delta f$, and the nyquist frequency $f_N = f_s/2$. If the user elects to use the special spectrum given above, he must also specify the wave height, H (in feet), the lowest harmonic, N_1, and the wave steepness, $\gamma = \frac{H}{L}$. The program then computes the following parameters:

$f_1 = N_1 \Delta f = \frac{N_1}{T}$	the lowest frequency of interest
$f_2 = \left(\frac{g\gamma}{2\pi H}\right)^{1/2}$	the breakpoint frequency
$L_1 = \frac{g}{2\pi f_1{}^2}$	the lowest equivalent deep water wave length in the spectrum

where g is the gravitational constant (=32.17 ft^2/sec). fmax has been set at 1.6 hertz. f_2 and L_1 are printed out for the operator to inspect. The spectrum is then defined using the above formula.

If the user wishes some other spectrum, he must specify the harmonic number, N, and the wave height, H, of each non-zero frequency component in the spectrum. The spectral density of this frequency component is given by:

$$G(N\Delta f) = \frac{H^2}{8\Delta f} = \frac{H^2 T}{8}$$

The user can define up to 40 or 50 such components depending on the frame length.

The second program (CONVRT) divides the desired spectrum by the magnitude squared of the transfer function to obtain the spectrum of the drive signal. On the initial pass thru this program, a default or generalized transfer function is used. On all other passes, a transfer function measured from the previous iteration is used. This gives a better measure of the transfer function in the amplitude range of interest. Next the program allocates a certain portion of the drive spectrum to the lower flap and the rest to the upper flap as a function of frequency using a prerecorded splitting table. These portions may be either in phase or 180 degrees out of phase depending on the data in the table.

The program has the capability of generating a variety of types of drive signals. Figure 3 shows the types of signals the program can produce. For regular tests the user can specify a single frequency or by specifying a number of frequency components and not randomizing the phase of each component the user can specify a more complex wave. In this case the phases are all set to zero. Both these types of drive

signal are possible by using one or more function generators and have been used traditionally in towing tanks.

The program has the additional capability of generating a class of drive signals known as 'pseudo-random'. Each drive signal consists of a series of groups of points known as frames. Each frame is calculated by taking the inverse Fourier transform of a spectra where the amplitude is determined by the drive spectral density and the phase is randomly selected. The operator may choose to randomize the phases only once, to rerandomize the phases every N frames, or to rerandomize them for each frame. These give the type of drive signals known respectively as periodic irregular periodic random, and random signals. Normally periodic irregular waves are used for ship model testing since random and periodic random signals require a larger number of averages for measurement accuracy while periodic irregular signals are completely defined by a single frame. For experiments such as off shore structure model tests where the carriage is stationary, random and periodic random signals can be used since longer averages are possible. "True random" testing with time varying amplitude components requires long term averaging to satisfy Chi-squared statistics. Although this type of testing has been used in towing tank work, the results suffer from large data scatter and poor reproducibility.

The operator can chose which type of drive signal he wants by specifying the number of independent and the number of dependent frames per independent frames in the drive signal. If he specifies one independent frame, the drive signal will be periodic irregular. If he specifies one dependent frame per independent frame, the drive signal will be random. Anything else will be a periodic random signal.

The third program (WAVE) drives the wave board with the newly created drive signal. The drive signal contains the highest frequency component contained in the signal in its header information. This allows the program to calculate the time for the shortest wave length to travel to the wave height sensor using the group velocity. The delay time t_d is given by the formula:

$$t_d = \frac{4\pi\ d f_{max}}{g}$$

where fmax is the highest frequency and d is the distance from the wave board to the sensor. The program will ignore all wave data until the largest frequency (shortest wave length) is present for at least 90% of the frame.

The operator has the option to only run the drive signal once or to repeat the drive signal indefinitely for long term testing.

The fourth program (PSD) analyzes the acquired data to determine the achieved spectral density. The operator has the option to "Hann" the data if desired. The achieved wave height spectrum is compared to the desired wave height spectrum on a frequency by frequency basis and errors greater than 2 dB (26% above the desired spectral density value or 20% below) are printed out. The operator may then elect to calculate a new transfer function to use for the next iteration to reproduce the desired sea state more accurately. The transfer function is calculated using the formula:

$$H\ (f_k) = \left(\frac{G_y(f_k)}{G_x(f_k)}\right)^{1/2}$$

where S_y and S_x are the spectrums of the achieved wave heights and drive signals respectively. This gives us the magnitude of the transfer function, though not the phase. Appendix A shows that this is a biased estimate of the transfer function, but it does give a ratio of output to input which allows the drive spectrum to be corrected in order to obtain the desired response.

By using a new transfer function, the operator can rerun the second program and obtain a new drive signal. This process will continue until, in the operators judgement, the desired spectrum has been duplicated.

The computer system was installed at the 120 foot tank at the U.S. Naval Academy and placed in operation in September of 1976. Because of irregular (random) waves of a short time duration were desired for towing tank testing, it was decided that, at that time, only periodic drive signals would be run. Two specified spectral densities were chosen such that the total energy in each spectrum was equivalent to the energy in a Pierson-Moskowitz spectrum with significant wave heights of .25 feet and .35 feet respectively. The defining parameters for the two spectra are:

	Spectrum 1	Spectrum 2
Frame Length T	20 sec	20 sec
Number of points per frame N	512	512
Lowest Harmonic N_1	7	10
Wave height H	.06642 feet	.05358 feet
Wave Steepness γ	2.1525E-4	1.7365E-4
Significant wave height in a P-M spectrum	.35 feet	.25 feet

Several things were noted during installation. First, for those single frequencies tested the harmonic distortion was minimized if the motion of the two wave flaps was such that the upper flap was kept vertical. That is the motions of the two flaps were 180° out of phase and the angles were kept equal. Secondly, in order for the system to converge to the desired spectrum, the frequency component phase angles selected for the initial drive signal must be duplicated on successive iterations. This is because harmonic distortions of the lower frequency components apparently add to the higher frequency components. If the phase relationships are changed between iterations the distortion may add to the higher frequency signal on the next iteration rather than subtract from it or vice versa. Also, because of this distortion during the iterative proceedure, the lower frequency components approach the desired value first, then the intermediate frequencies, and finally the higher frequency components. Figures 4 - 6 show the results of the first three runs for spectrum 2 and show this phenomena.

Figure 7 shows the desired spectrum 1 overlayed with the achieved spectrum. Figure 8 shows the same for spectrum 2. The achieved spectra are within 1 dB of the desired at all frequency values on figure 8 and within 0.5 dB of the desired on figure 7. The errors in wave energy is .8% for spectrum 1 and 1.8% for spectrum 2. Figure 7 represents the results after 7 iterations although the 2 dB limit was reached on the third pass. Figure 8 represents the results after four iterations. Note also that the achieved spectra drop off quite rapidly outside of the range of interest.

These plots show that the technique discussed above is a viable one for duplicating wave spectra in a tank equipped with a servo-hydraulic wavemaker. Neither of the drive signals caused breaking waves in the tank, although at several times the waves would seem to be almost ready to break. In both examples, a new drive signal was ready for the next iteration before the tank had settled and in both cases the spectra were duplicated within two hours of its initial definition. Thus several reproducible sea states may be set up for a test in a reasonable amount of time.

References

1. Johnson, B., "A Proposed Irregular Wave Spectrum for Model Tests in Towing Tanks", Proceedings of the 17th ATTC, Pasadena, Calif.

2. Springett, C.N., Chen, K.K, Biewer, F.N., "Anomalies in the Response of Semisubmersibles", Proceedings of the 1976 Offshore Technology Conference.

APPENDIX A

$|\hat{H}(f)|$ is measured using the formula

$$|\hat{H}(f)| = \left(\frac{Gyy(f)}{Gxx(f)}\right)^{1/2}$$

where the ^ symbol means that $\hat{H}$ is an estimate of H. Then

$$Gyy = Gyx\ H^{*}$$
$$|Gyy|^2 = |Gyx|^2 |H|^2$$

and

$$|\hat{H}(f)| = |H(f)| \left(\frac{|Gyx|^2}{GxxGyy}\right. = |H(f)|\ \gamma^2_{yx}$$

where γ^2_{yx} is the coherence function between the input x and the response y. Thus $|\hat{H}(f)| = |H(f)|$ only if $\gamma^2_{yx} = 1$. If $\gamma^2_{yx} < 1$, $|\hat{H}(f)|$ will not approach the true value $|H(f)|$ and thus it is a biased estimate.

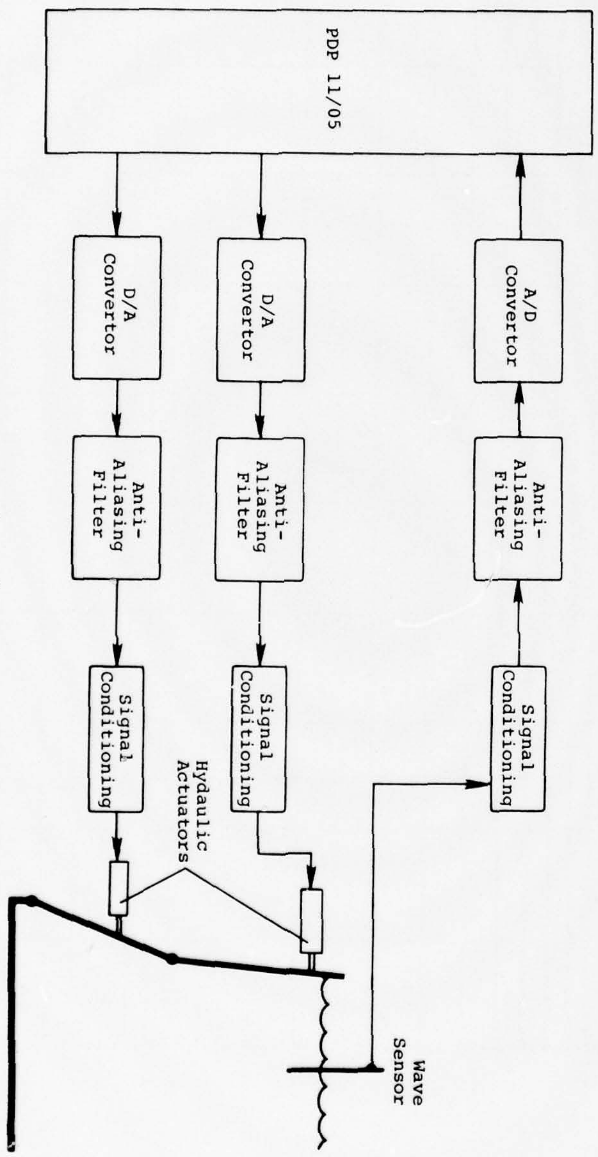
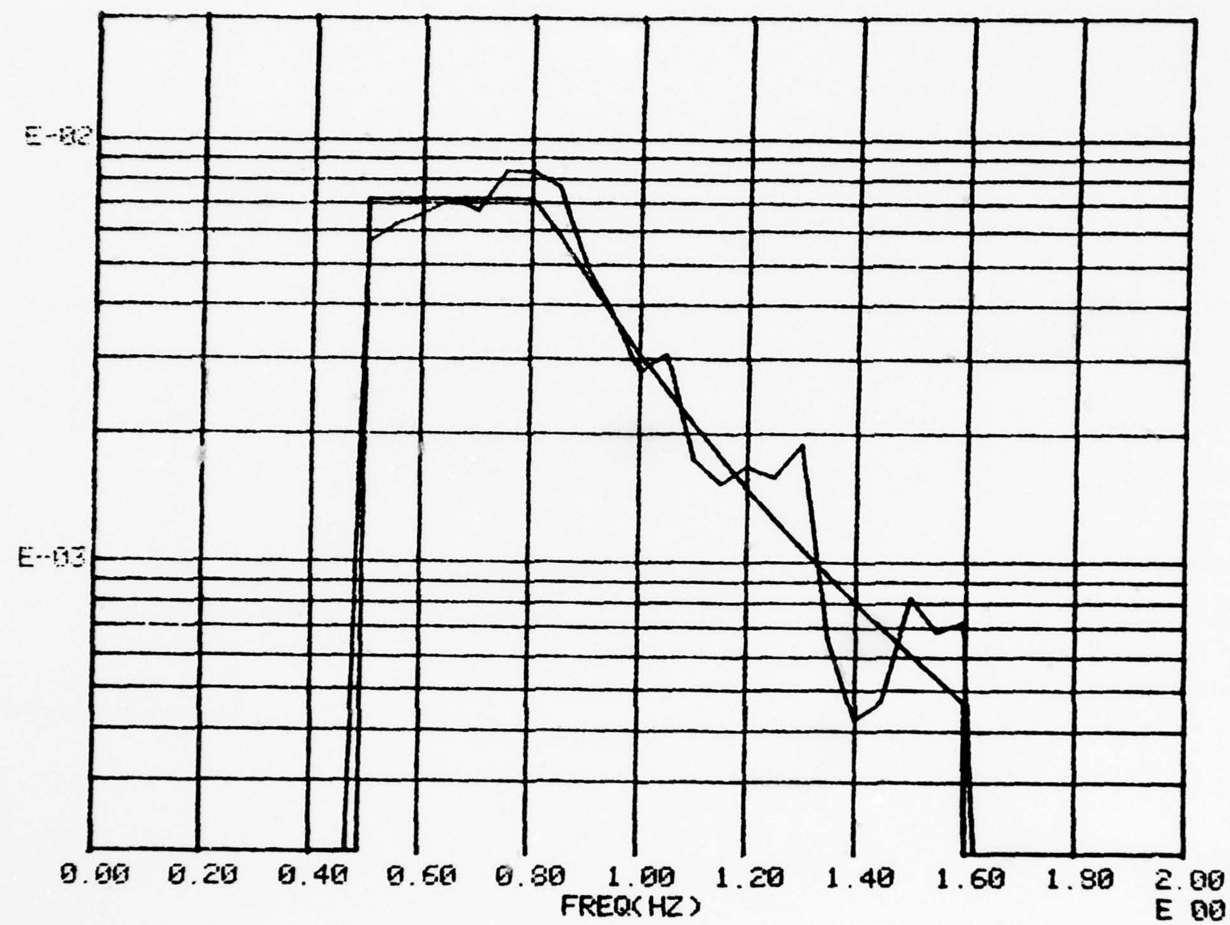

PDP 11/05
D/A Convertor
D/A Convertor
A/D Convertor
Anti-Aliasing Filter
Anti-Aliasing Filter
Anti-Aliasing Filter
Signal Conditioning
Signal Conditioning
Signal Conditioning
Hydaulic Actuators
Wave Sensor

Figure 1

Figure 4

Desired and achieved wave height spectrums first run - Spectrum 2



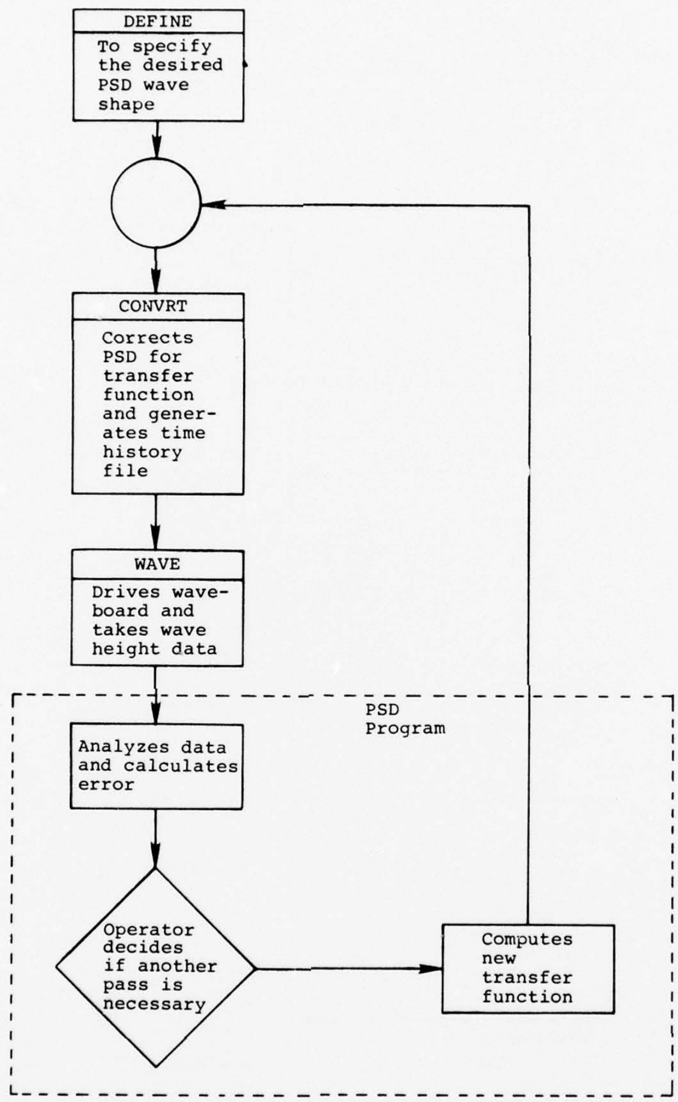

DEFINE
To specify the desired PSD wave shape
CONVRT
Corrects PSD for transfer function and generates time history file
WAVE
Drives wave-board and takes wave height data
PSD Program
Analyzes data and calculates error
Operator decides if another pass is necessary
Computes new transfer function

Figure 2

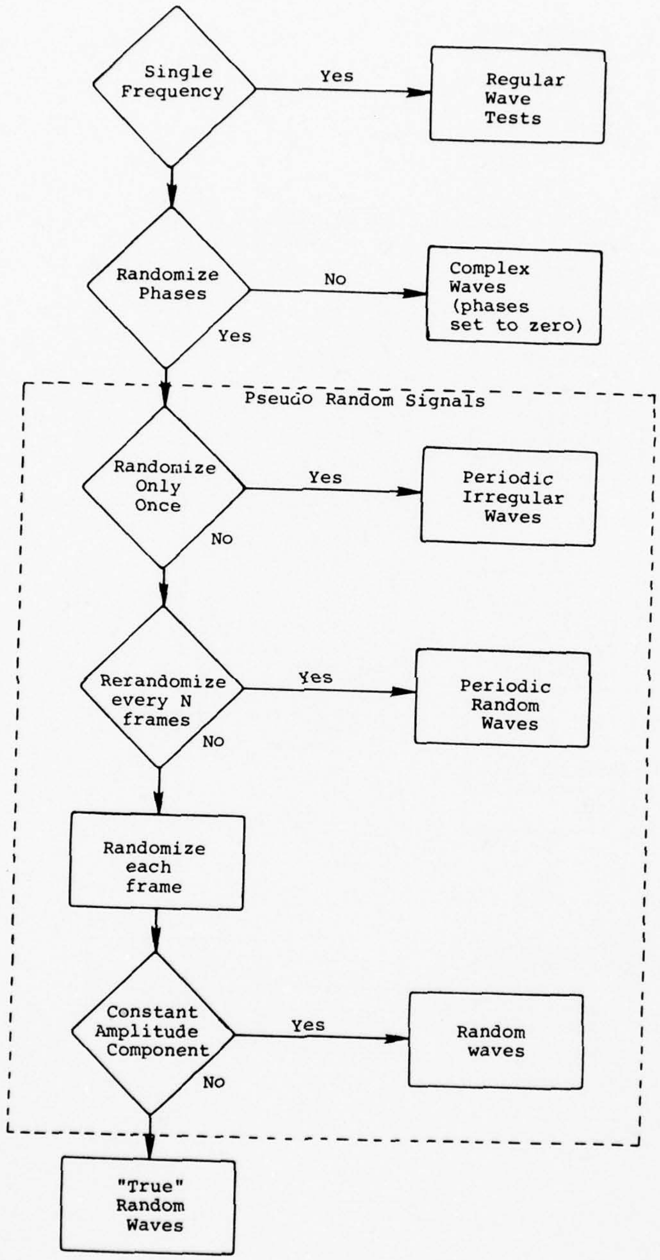

Single Frequency
Yes
Regular Wave Tests
Randomize Phases
No
Complex Waves (phases set to zero)
Yes
Pseudo Random Signals
Randomize Only Once
Yes
Periodic Irregular Waves
No
Rerandomize every N frames
Yes
Periodic Random Waves
No
Randomize each frame
Constant Amplitude Component
Yes
Random waves
No
"True" Random Waves

Figure 3

Figure 5

Desired and achieved wave height spectrums on second run - Spectrum 2

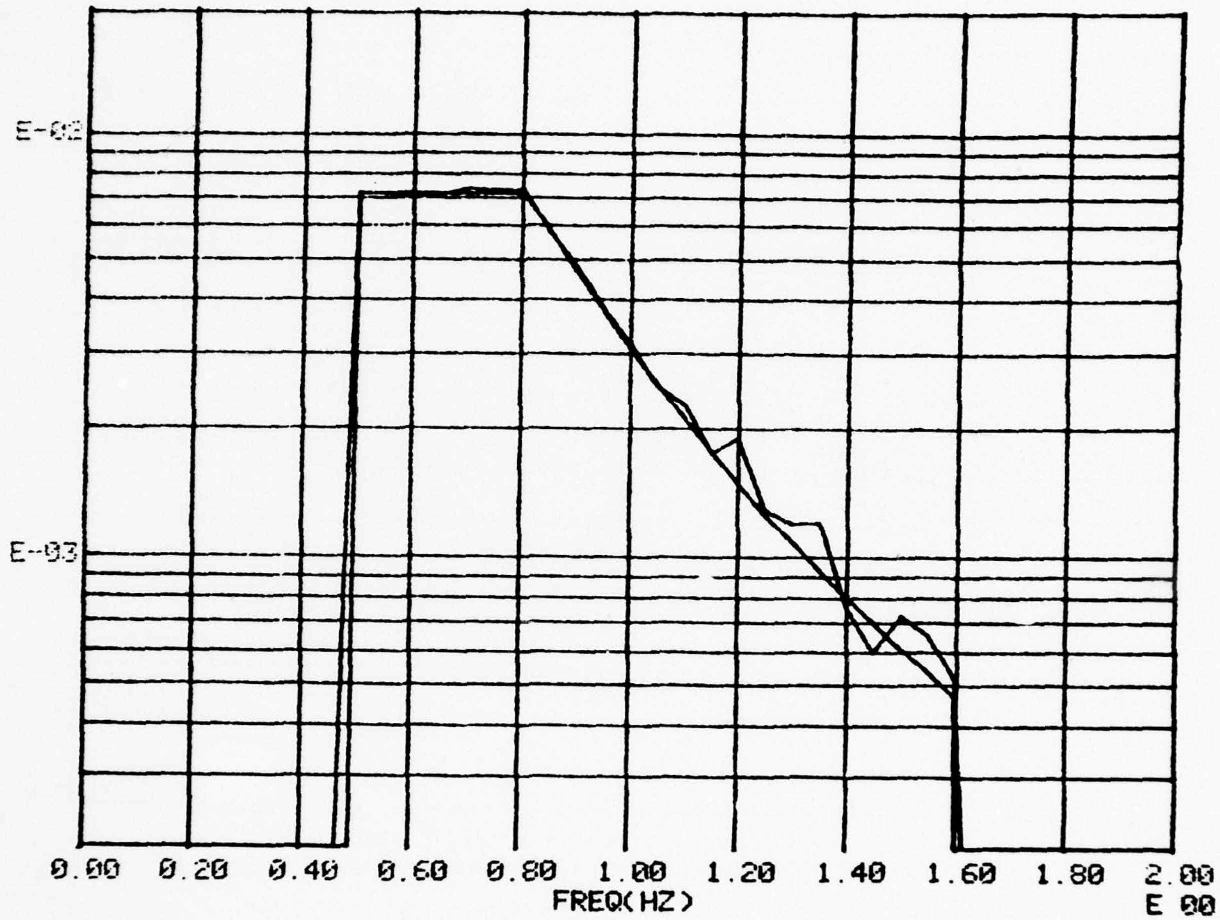
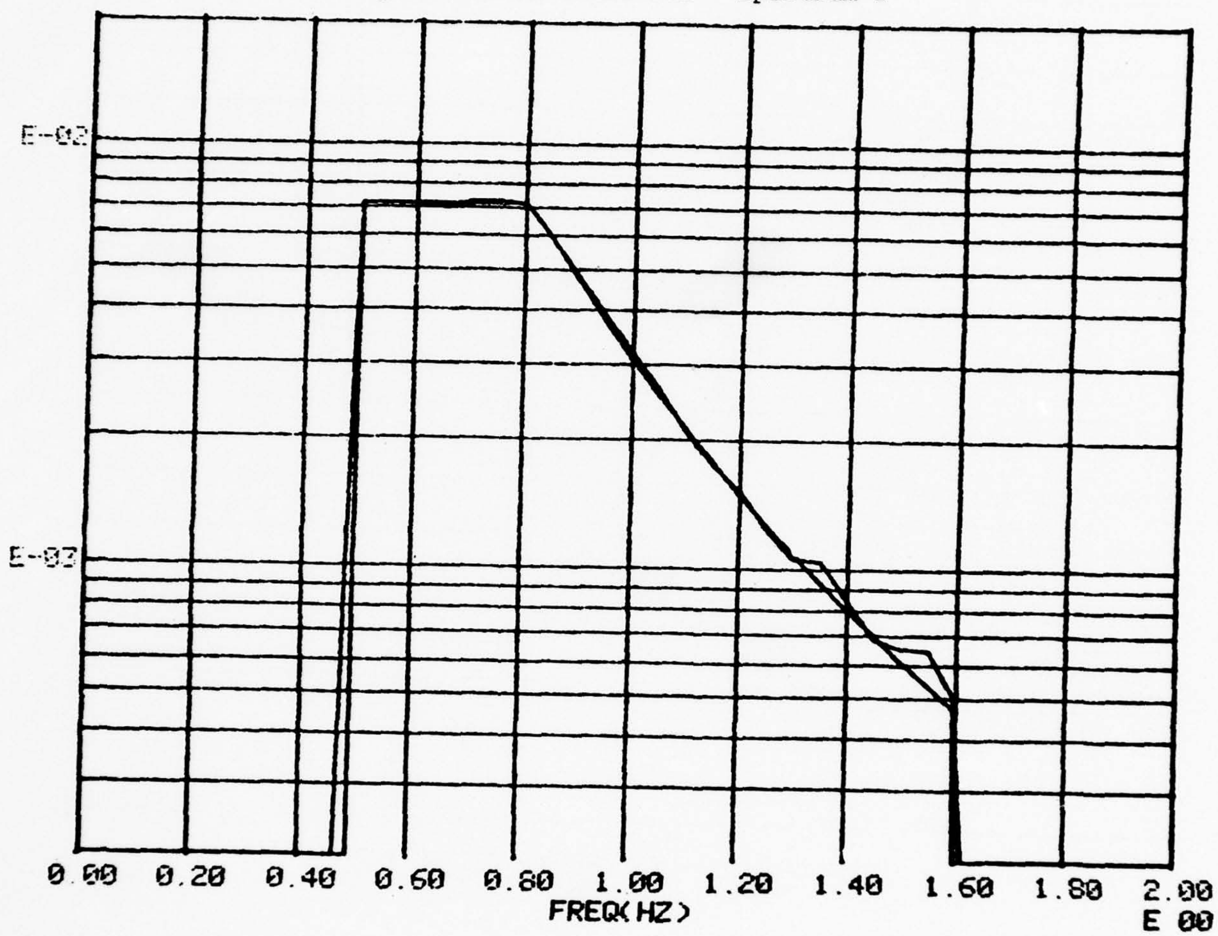


Figure 6

Desired and achieved wave height spectrums on third run - Spectrum 2



Desired and Achieved Waye Spectral Density

Significant Wave Height = .35 feet

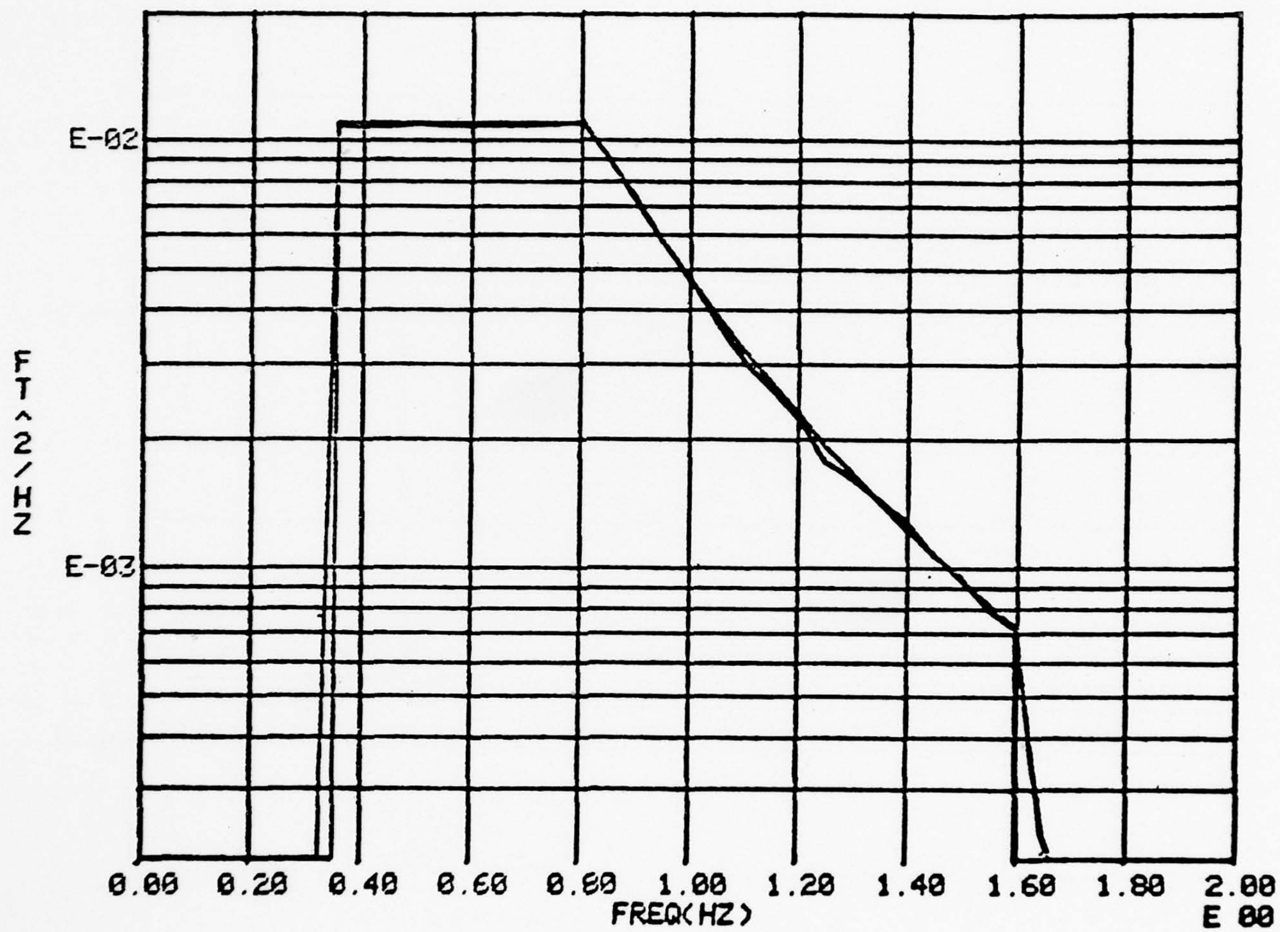


Figure - 7

Desired and Achieved Wave Spectral Density

Significant Wave Height = .25 feet

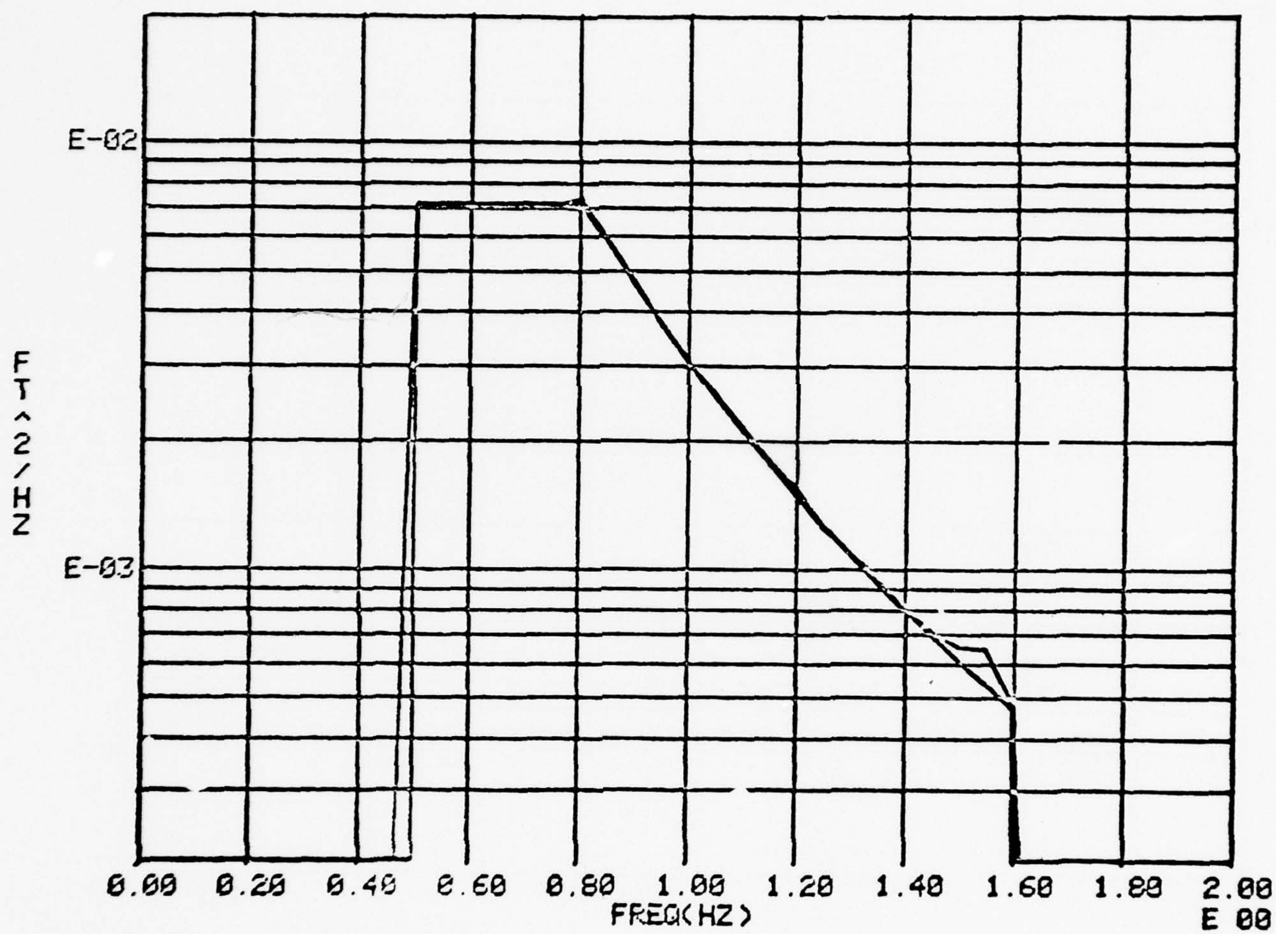


Figure - 8

DIGITAL CONTROL OF D.C. TOW TANK DRIVES

WITH PHASE-LOCKED LOOP TECHNIQUES

by Richard H. Osman
Robicon Corporation
Pittsburgh, PA 15239

SUMMARY

Recent development of complex functions in the CMOS logic family through medium scale integration have permitted the design of very accurate digital speed control circuits which are also relatively simple, inexpensive, and highly noise immune. The purpose of this paper is to review the application of this kind of digital speed control to tow tank drives where extraordinary accuracy and repeatability are required. The fundamental control technique of phase-locking an incremental tachometer pulse train to a command pulse train will be described. The methods of generating and controlling the command pulse train will be covered, including special techniques for handling rotary arm tanks. Implementation of acceleration and deceleration controls, as well as the means of direct digital speed readout will be described. Interfacing of these digital controls with two types of DC drive systems will be shown. A general system block diagram based upon a thyristor dual converter will be presented. Systems considerations of retrofitting existing motor-generator type drives by replacing amplidynes with thyristor field exciters will be discussed. The paper will conclude with a summary of the advantages to be obtained by using digital control of D.C. drives. Some rough cost figures for typical systems will be given.

DIGITAL CONTROL OF DC TOW TANK DRIVES WITH PHASE LOCKED LOOP TECHNIQUES

by

Richard H. Osman

Robicon Corporation
Pittsburgh, PA
412-327-7000

The introduction of complementary metal oxide semiconductor logic circuits in the early seventies heralded an era of rapid growth in the application of digital control to industrial control applications. The facility with which medium scale integration of logic functions can be accomplished in the CMOS technology resulted in the rapid growth of these logic circuits such that quite complex functional blocks have been available for three or four years now. These logic circuits are inexpensive and very noise immune, which are two highly desirable qualities for a commercial or industrial control system. These integrated circuits found immediate application in the digital control of rotary motion systems, since a number of logic functions were specifically intended to control and process pulse trains such as would be generated by an incremental tachometer on a motor. The inherent accuracy of digital controls and their relative insensitivity to drift and aging, as compared to analog controls, suggested their use in speed control systems where extraordinary accuracy and repeatability are required. One example of this sort of variable speed drive is a tow tank drive, which is in itself a highly complex, sophisticated piece of test equipment. The variable speed drive used to power the carriage and/or the model should, therefore, contribute as little uncertainty to the test situation as possible. In this regard, it is highly desirable to have drives which are capable of a high degree of absolute accuracy and repeatability. Other desirable characteristics are the ease of incorporating acceleration and deceleration controls into the circuit and providing for some sort of speed indicating means. A typical requirement for speed control for a tow tank drive might require .1 to 100 fps in steps of .001 fps, with an absolute accuracy of $\pm$.005% of top speed, with independent forward and reverse acceleration and deceleration controls. The system should be capable of being scaled in any units which the customer may require and it should be conveniently capable of reversing to provide return of the carriage or model to the starting position. It should also, of course, be rugged and reliable and accept extremes of ambient conditions from zero to 40°C with the possibility of 100% relative humidity.

The fundamental control technique utilized to achieve the extreme speed accuracy is generally known as phase locking. In this type of control the motor is equipped with a pulse tachometer which generates 600 to 1200 pulses per revolution. This tachometer basically provides both speed and position information relative to the angular motion of the motor shaft. Each pulse represents an incremental angle of advance of the motor shaft and the repetition rate of the pulses is directly proportional to the motor speed. The speed reference for this type of system is a crystal based oscillator which has extremely good temperature stability and very low aging. Typically, these temperature compensated crystal oscillators have an accuracy of two or three parts per million and a temperature stability of one part per million over the range of zero to $50^{\circ}C$. The exact value of reference frequency F1 is determined by a number of essentially arbitrary factors, including the dimensions or measuring units of the system, gear ratios, drive wheel diameters, and the choice of units. Therefore, in devising the master clock circuit we have necessarily provided an adjustment means of wide range and at least .01% resolution, in order to accommodate a variety of systems.

For rotary arm tow tanks the speed set is usually required to be accomplished in peripheral speed, while the motor speed control is in terms of angular velocity. Therefore, we have developed special circuits to radius compensate the master clock signal. These circuits accept a thumbwheel switch input calibrated in the radius of the arm directly and they provide an inverse multiplication function on the output of the master clock circuit, so that it is adjusted to compensate for radius before it is fed into the rate multiplier circuit.

The extremely stable master clock frequency is processed by a digital circuit which multiplies the frequency by some arbitrary adjustable factor between zero and 1.9999 and a final reference frequency (F3) is then obtained, which is scaled on a one to one basis with the pulse tachometer frequency. That is to say, if we wish the motor to run at 1800 rpm which corresponds to 36 KHz tachometer pulse train, we must generate from our master clock and rate multiplier a 36 KHz reference signal.

The rate multiplier is the speed setpoint control in the system. The inputs are 4 or 5 decade thumbwheel switches which control the CMOS rate multipliers. The rate multiplier string performs a frequency multiplication on the input, F2, where the output, F3, is equal to F2 x .ABCDE, where ABCDE are the thumbwheel switch settings. The rate multipliers can generate any factor between zero and 1.9999. In various applications, top speed may correspond to various arbitrary numbers so that the clock input to the rate multiplier must be selected so that at

the top speed setting of the thumbwheel switches, the rate multiplier output, F3, is exactly equal to the pulse tachometer frequency at top speed.

This reference signal can be thought of as a position reference. The two pulse trains are fed into a phase lock circuit. The reference pulse train causes a twelve-bit binary up-down counter count down. This is, in effect, digital integration. The counter contents are then proportional to the angular position difference between the reference and the motor. The information generated by the counter can then be used to take corrective action in the drive to maintain the motor speed in absolute correspondence with the reference frequency. Basically, by controlling position, which is the integral of velocity, we can regulate the velocity to zero error.

In order to conveniently interface these digital controls with a practical variable speed drive, the analog controls in the usual thyristor drive are retained. The block diagram of the thyristor dual converter phase lock drive, Fig. 1, shows how this is done. The reference frequency, F3, is converted by an F/V converter to an analog signal proportional to the desired motor speed. This is processed by a rate limit circuit, whose inputs are the accel/decel controls.

The acceleration/deceleration controls are generally implemented by analog circuits, since the absolute accuracy of acceleration/deceleration is not required to be as great as that for speed. Typically, an accel/decel control accuracy of 1% is achieved. The rate limit circuit is interposed between the command F/V converter and the speed error amplifier of the drive system, be it armature converter or field converter.

This rate limited analog speed command signal becomes the reference signal for the speed error amplifier. Meanwhile the tachometer pulse train passes through a similar frequency to voltage converter. The resulting analog speed feedback signal then is subtracted from the speed reference signal and the difference is amplified by a speed error amplifier. The output of the phase lock circuit is added in on top of the speed feedback signal. The output of the speed error amplifier is a torque or current reference for the variable speed drive.

Here the control can take either of two configurations. The variable speed drive may consist of a thyristor dual converter driving the motor armature, as shown in Fig. 1. In this case, the output of the speed error amplifier is a current reference signal which is compared to the actual motor armature current and the difference is amplified, which then becomes an input to

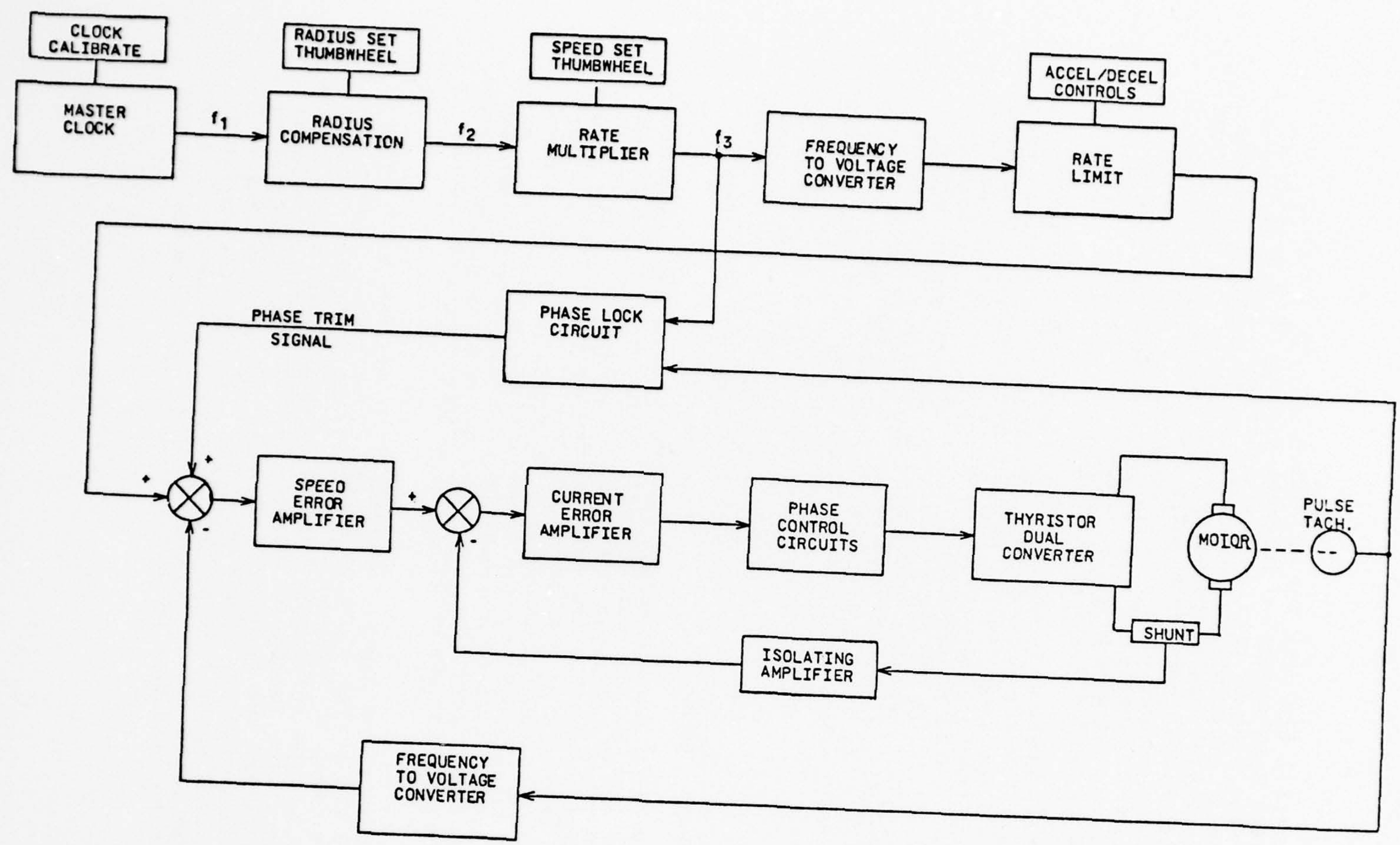


FIG. 1 BLOCK DIAGRAM OF PHASE LOCKED VARIABLE SPEED DRIVE

the phase control circuits for the drive. Thyristor dual converters, while more expensive in large systems than a retrofit motor-generator system, provide the ultimate in response because of their speed. The internal current loop in a thyristor dual converter typically has a crossover frequency of 500 radians per second, which means that for a small disturbance the armature current can be changed with a time constant of about 2 milliseconds. Simultaneously, the speed loop of such a system can have a crossover frequency of 50 radians per second. The analog systems in such a drive have an accuracy of 1% of top speed.

For those systems in which a large motor-generator set already exists as the prime mover, we can build a retrofit system which has the same digital control as previously described, but in which the thyristor dual converter driving the armature of the motor can be replaced with a thyristor dual converter driving the field of the main generator. See the next block diagram, Fig. 2. Here the motor armature current is sensed by an isolating amplifier and compared to the current or torque command coming out of the speed error amplifier. The current error is processed by an operational amplifier with proportional and integral gain, and the resulting signal is used as a field current command. The field of the main generator is excited by a small SCR dual converter, usually single phase, with a capacity of up to 25 Amps. This thyristor dual field converter has its own internal field current feedback and is a completely self-contained unit.

We can also provide single ended thyristor field converters to provide precison current control of the motor field current. Systems in which more than one motor are operated from the same master DC generator require current sharing circuitry to adjust the field currents of the individual motors. This is a minor addition to the control circuitry. A retrofit digital control replacing an amplidyne system can be purchased at a modest cost compared to the cost of a new motor-generator type system, or at somewhat less cost than replacing the motor-generator system with a new armature converter drive of the same size, above 100 hp.

Because speed information exists in the form of a pulse train and the system contains a precision crystal oscillator, it is very easy to implement digital speed measuring circuits with L.E.D. type readouts. This is accomplished in the following manner. The tachometer pulse train is fed into a counter which totalizes the tachometer pulses over a precise interval called the time base. The time base is chosen such that at some specific speed in a given system of units, the number of tachometer pulses is numerically equal to the speed. This results in the time base usually having an odd value for systems

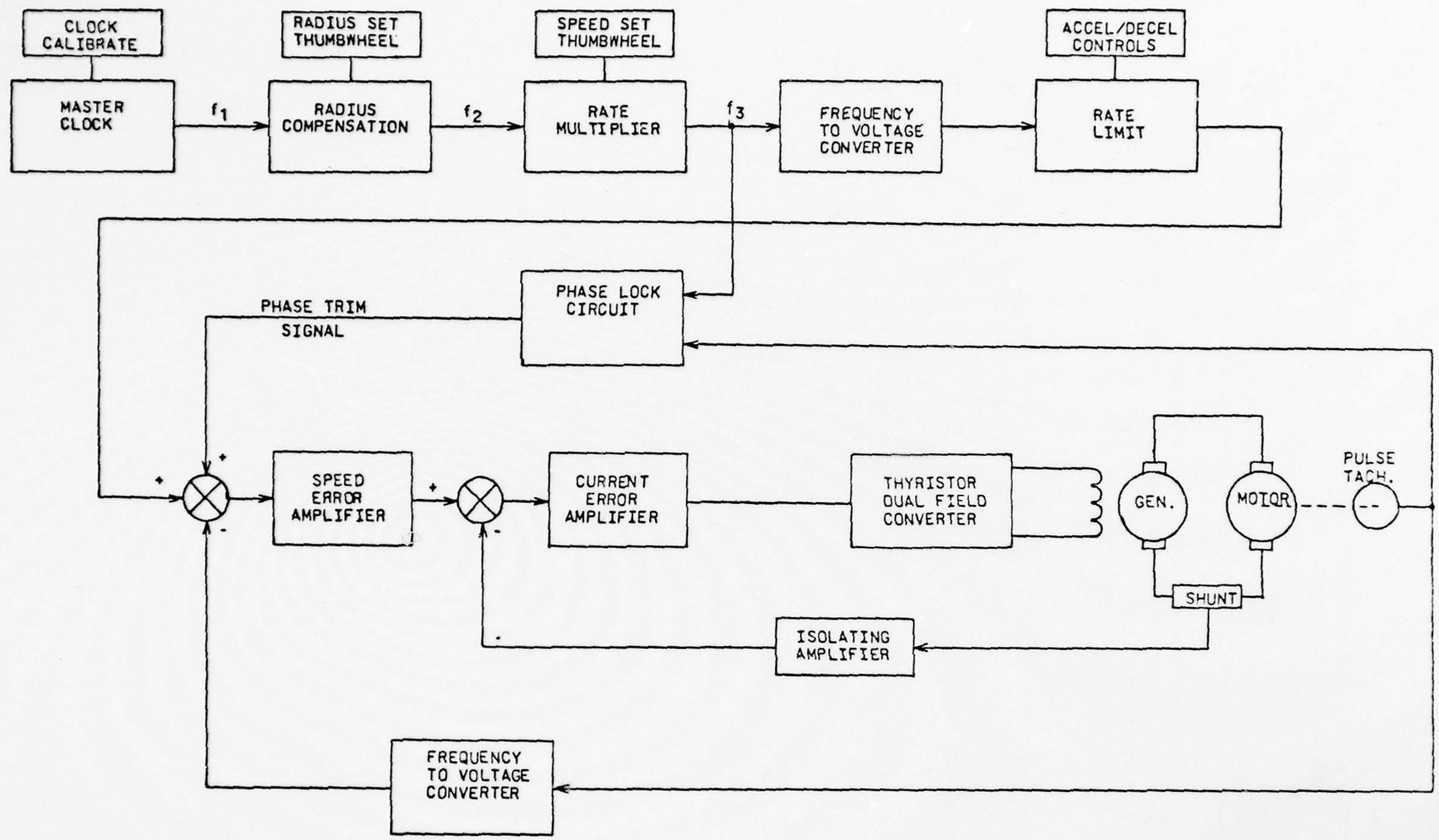


FIG. 2 BLOCK DIAGRAM OF PHASE LOCKED VARIABLE SPEED DRIVE

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in which the drive wheels and gear ratios are odd values. However, the output of the master clock bears a fixed power of ten relationship to the time base. Generally, to read the speed to the level of accuracy required results in a time base of substantial length. For instance, suppose we have a system which generates a 36 KHz pulse train at top speed of, for example, 100 fps. If we wish to measure the speed accurate to .01 fps, then we must accumulate 10,000 tachometer pulses from a pulse train of 36 KHz. This requires that the time base be 10/36 of a second, or approximately three speed samples per second. As a rule of thumb, more resolution requires a longer sampling period.

In review, the primary advantages of digital control of DC drives are that, first and foremost, the digital control technique provides extreme accuracy of control. This type of control is also readily interfaced with the digital output of a computer. The control provides very fast response and smooth, precision controllable acceleration and deceleration controls. Furthermore, rotary arm tanks can be scaled in peripheral speed and acceleration variables without undue difficulty. Digital means of speed indication can easily be included in the system. Finally, the DC variable speed drive is the simplest, most reliable type of variable speed drive available at this time. Therefore, the combination of the latest digital hardware with the time-tested, reliable, rugged DC variable speed drive has proved to be an extremely powerful combination for precision speed control.